

Impact response of US Army and National Football League helmet pad systems

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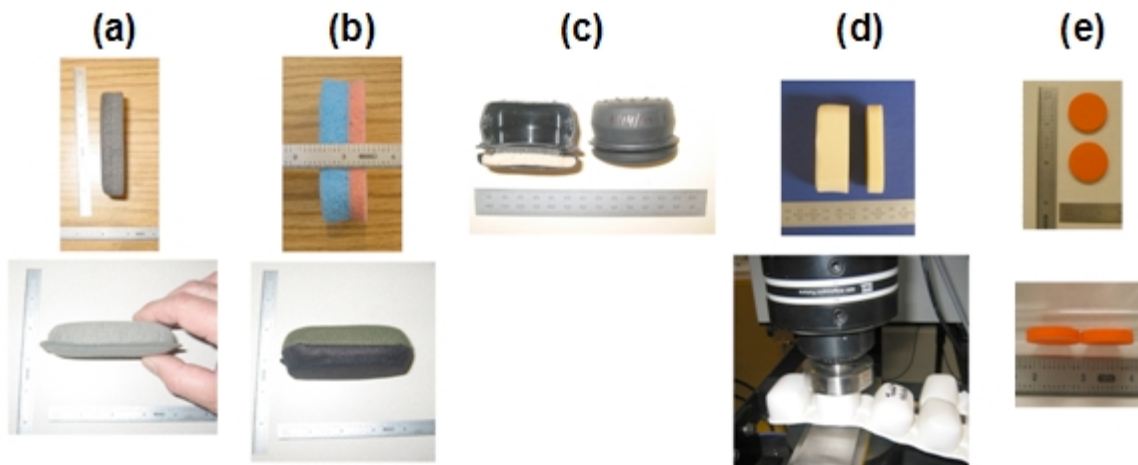
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Executive Summary

Lawrence Livermore National Laboratory [LLNL] was tasked to compare the impact response of NFL helmet pad systems and U.S. Army pad systems compatible with an Advanced Combat Helmet [ACH] at impact velocities up to 20 ft/s. This was a one-year study funded by the U.S. Army and JIEDDO. The Army/JIEDDO point of contact is COL R. Todd Dombroski, DO, JIEDDO Surgeon. LLNL was chosen by committee to perform the research based on prior published computational studies of the mechanical response of helmets and skulls to blast. Our collaborators include the U.S. Army Aeromedical Research Laboratory [USAARL] (a DoD laboratory responsible for impact testing helmets), Team Wendy and Oregon Aero (current and former ACH pad manufacturers), Riddell and Xenith (NFL pad manufacturers), and d3o (general purpose sports pad manufacturer).

The manufacturer-supplied pad systems that were studied are shown in the figure below. The first two are the Army systems, which are bilayer foam pads with both hard and soft foam and a water-resistant airtight wrapper (Team Wendy) or a water-resistant airtight coating (Oregon Aero). The next two are NFL pad systems. The Xenith system consists of a thin foam pad and a hollow air-filled cylinder that elastically buckles under load. The Riddell system is a bilayer foam pad that is encased in an inflatable airbag with relief channels to neighboring pads in the helmet. The inflatable airbag is for comfort and provides no enhancement to impact mitigation. The d3o system consists of a rate-sensitive homogeneous dense foam.



Pad systems studied: (a) Team Wendy; (b) Oregon Aero; (c) Xenith; (d) Riddell; (e) d3o

LLNL performed experiments to characterize the material properties of the individual foam materials and the response of the complete pad systems, to obtain parameters needed for the simulations. LLNL also performed X-ray CT scans of an ACH helmet shell that were used to construct a geometrically accurate computational model of the helmet.

Two complementary sets of simulations were performed. The first set of simulations reproduced the experimental helmet impact certification tests performed by USAARL, who provided data for comparison. The goal of this set of simulations was to demonstrate the overall validity of LLNL's computational analyses and methods and understand the general physics of helmet impacts. In these tests and the corresponding simulations, an inverted ACH containing pads and a head-form are dropped onto a hemispherical anvil, at 10 and 14.14 ft/s impact velocities. The simulations predicted peak accelerations (the metric used by USAARL for comparing the performance of pad systems), rebound velocities, and impact durations consistent with the experimental data, thus demonstrating the validity and relevance of the simulation methods.

Because the NFL pad systems are approximately double the thickness of the U.S. Army pads, they do not fit into the ACH. As a result, the NFL pads could not be simply placed into an ACH shell in either a simulation or an experiment without modifying their size and shape. Since impact mitigation depends critically on the available stopping distance and the area over which the stopping force is applied, it is important to consider identically shaped pads in order to compare their performance in a fair and meaningful manner. Consequently, the second set of simulations utilized a simplified simulation geometry consisting of a 5 kg cylindrical impactor (equal in mass to a head) striking equally sized pads from each manufacturer. The simulated bilayer foam pads had the same proportions of hard and soft foam as the actual pad systems, while the Xenith pads were simulated as a bilayer foam pad with material properties adjusted to give the same response as the actual Xenith pads. The effects of trapped air were included in the simulations of the Team Wendy and Oregon Aero pads. All simulations used material properties derived from the experiments conducted at LLNL.

The acceleration history of the center of mass of the impactor was used to calculate the Head Injury Criterion (HIC) for each simulation, to assess the pad performance. The HIC is a well-established metric that combines both acceleration and duration of impact to assess the danger of injury, and is a more robust measure than peak acceleration.

Our key findings are:

- 1. The performance of a pad depends on the range of impact velocities. At lower impact velocity, softer pads perform better. At higher impact velocity, harder pads perform better.**
- 2. Thicker pads perform better at all velocities, but especially at high velocities.**
- 3. For comparable thicknesses, neither the NFL systems nor the Oregon Aero pads outperform the Team Wendy pads currently used in the ACH system in militarily-relevant impact scenarios (impact speeds less than 20 ft/s).**

The second finding suggests a commercial off-the-shelf solution for mitigating impact-related traumatic brain injury to soldiers. By simply using helmet shells that are at least one size larger with thicker pads, the injuries from impacts, especially severe impacts, may be reduced significantly.

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1. Overview and Background

1.1 Motivation

Impacts caused by IED attacks and other hazards in the field cause significant occurrences of traumatic brain injury [TBI] in deployed soldiers. Helmets do not completely protect against TBI.

The effectiveness of a helmet at protecting against impact-induced TBI is strongly influenced by the helmet pads. Since impact-induced TBI is also of interest to the NFL, there was interest in how helmet pads used by the NFL would perform in militarily-relevant impact scenarios, as compared to pads used in U.S. Army helmets.

Because of prior experience studying the response of helmets and skulls to blasts [1], Lawrence Livermore National Laboratory [LLNL] was chosen to perform a computational study comparing the expected impact response of selected football pads to U.S. Army helmet pads.

1.2 Objective

The objectives of the study are:

1. Gain insight into the factors that govern how a pad protects against impact-induced TBI.
2. Determine if any other pad, especially the pads used by the NFL, protects against impact better than the Team Wendy pads currently used in U.S. Army helmets.
3. Identify solutions that could be implemented that would better protect soldiers from impact-induced TBI.

1.3 Systems Studied

Pad systems from five different manufacturers were considered:

- Team Wendy, which makes the currently used U.S. Army pad, consisting of a bilayer foam with a water-resistant air-tight wrapper
- Oregon Aero, which makes the formerly used U.S. Army pad, consisting of a bilayer foam with a water-resistant air-tight coating
- Xenith, which makes a pad used in football helmets, consisting of an elastically buckling air-filled structure with a thin foam pad

- Riddell, which makes a pad used in football helmets, consisting of a bilayer foam inside an inflatable casing with air relief channels
- d3o, which makes pads for use in protective sporting equipment composed of a dense homogeneous rate-sensitive foam

These systems are shown in Figure 1.

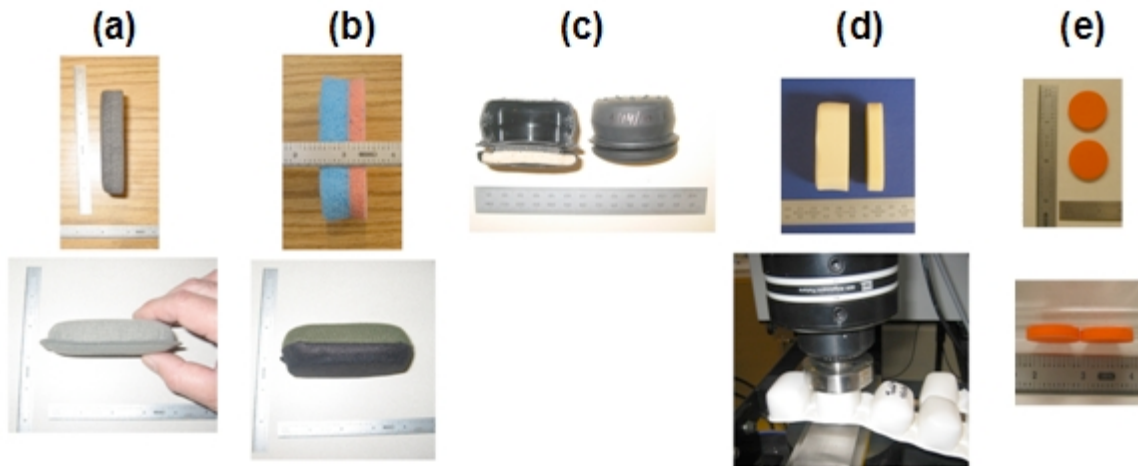


Figure 1 – Pad systems studied: (a) Team Wendy; (b) Oregon Aero; (c) Xenith; (d) Riddell; (e) d3o

1.4 Collaborators

LLNL worked with several collaborators in conducting this study.

The U.S. Army Aero Research Laboratory [USAARL] has conducted various impact tests on infantry helmets with various foam padding, and shared their data from these tests.

Team Wendy, Riddell, Oregon Aero, and Xenith all provided samples of their foam pad systems directly to LLNL. The d3o samples were sent to LLNL by our DoD funding point of contact. In most cases, the suppliers also provided technical insight into how their pads were intended to operate. Team Wendy also provided material test data for their pad materials.

1.5 Funding

This study was funded jointly by the U.S. Army and the Joint IED Defeat Organization [JIEDDO] through COL R. Todd Dombroski, DO, JIEDDO Surgeon.

2. Simulations of USAARL Crown Impact Experiments

2.1 Description of Experiment

We simulated crown impact experiments performed by USAARL [2],[3] and compared our simulations to the USAARL data [4], to establish the credibility of our computational methods. Figure 2 shows the typical experimental configuration [2], which consists of a magnesium alloy headform that is secured by a tightly cinched chinstrap to an Advanced Combat Helmet [ACH] (with pads). The headform is on a gimbaled mount that is attached to a vertical track by a metal arm. The weight of the headform and arm is approximately 5 kg. The gimbaled mount allows the selection of arbitrary impact points on the helmet. The headform is constrained by the arm and track to move only in the vertical direction. Although the tightly cinched chinstrap and resulting constrained motion may not be representative of actual impact conditions, they do provide a well-defined experimental configuration. The helmet/arm system is dropped from a height that is sufficient to overcome the small amount of track friction so that the desired impact velocity is achieved. Impact velocities range from 5-20 ft/s.

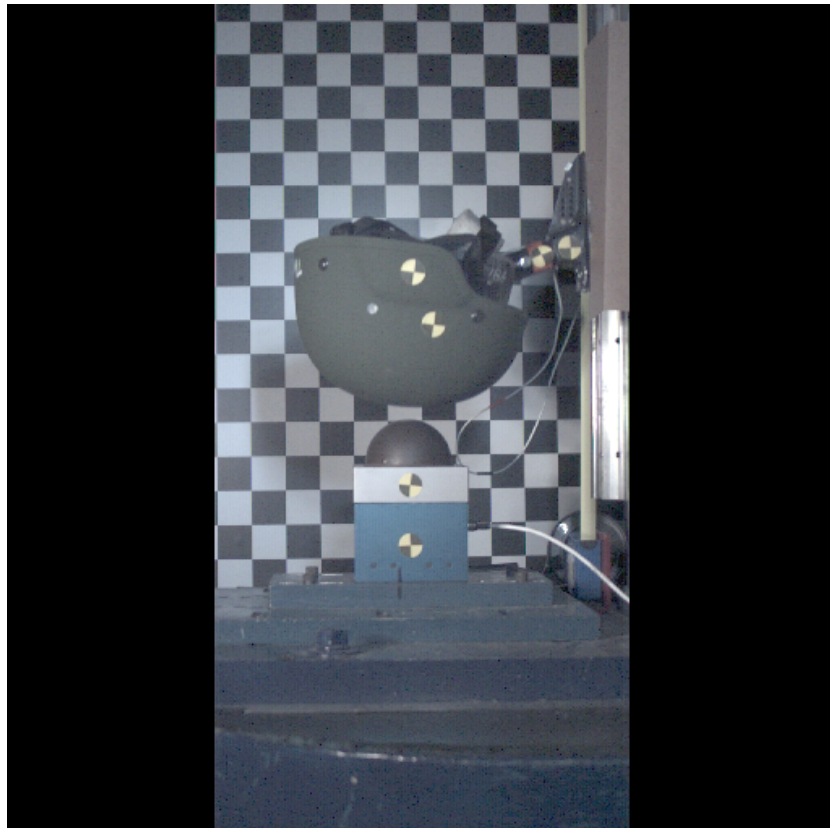


Figure 2 – Snapshot of a 14.14 ft/s crown impact on a hemispherical anvil

The traditional metric used by USAARL (and others) to assess the severity of an impact is the peak acceleration of the center-of-mass of the headform.

2.2 Description of Simulation

The experiment described above consists of a Kevlar™ ACH shell, foam pads, a magnesium alloy headform, a steel anvil, and air trapped inside the pad coverings. The experiment is simulated using finite element analysis [FEA]. In a finite element analysis simulation, each material is divided into small regions called “elements,” which comprise a mesh. For example, Figure 3 shows a meshed pad. Elements that touch can interact with each other.

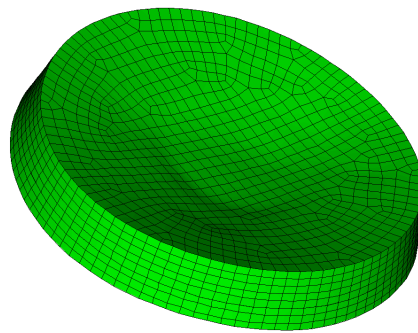


Figure 3 – Meshed pad

Conditions describing the impact, such as initial velocities and constraints on the motion of certain materials, must be specified. In the simulations of the USAARL experiments, the helmet, pads, and headform have an initial downward velocity. The base of the steel anvil is constrained so that it cannot move. Non-vertical motion of the headform is not constrained (contrary to experiment), because the simulation begins just as the impact is about to occur, and non-vertical headform motions are not expected to significantly affect the response.

The computer calculates the dynamic interactions of each element according to the laws of physics, and the subsequent response and motion of the entire system is determined over many small time increments. The particular physics engine used for these simulations is the finite element analysis software PARADYN, which is a massively parallel version of the LLNL-developed FEA software DYNA3D. “Massively parallel” implies that the software has been specially optimized to run on LLNL’s large supercomputers, which allows larger and more detailed simulations to be conducted.

The simulations accurately represent the actual geometries of the components. The helmet mesh was constructed by performing an X-ray computed tomography [CT] scan on an ACH shell, which was used to develop a 3D representation of the helmet shell geometry. This 3D model was then smoothed and meshed. The

headform geometry was created from drawings available from the manufacturer. The pad geometry was obtained by measuring manufacturer-supplied samples. Complete descriptions of these procedures are given in Appendix A.

In order to simulate the experiment, the FEA software must know how each material behaves when load is applied. This behavior is referred to as a “material model”, and is characterized by a set of material properties. Material properties for the Kevlar™ helmet shell were obtained from the literature [5]. Although the helmet shell is anisotropic, our simulations showed no substantial difference in the impact response between isotropic and anisotropic representations of the helmet. Consequently, all the simulations discussed in this report treat the Kevlar™ shell as an isotropic material, which simplified subsequent analyses of the effects of impact-induced plastic deformation of the Kevlar™. The material properties for the magnesium K1-A alloy used in the headform were obtained from efunda.com; this material was treated as elastic with Young’s modulus $E = 44.8$ GPa, Poisson’s ratio $\nu = 0.35$, and density $\rho = 1.8$ g/cc. Material properties for the foam pads were obtained from low and high strain rate unconfined compression tests that were performed at LLNL. The properties for each foam material were obtained by fitting the foam material model in PARADYN to these experiments. The details of the foam characterization experiments and the foam material model are given in Appendix B. During testing it was discovered that the coating/covering of the Team Wendy and Oregon Aero pads trapped air, which contributed significantly to the mechanical response of the complete pad. Appendix C describes how the effect of trapped air was included in the simulations.

Figure 4 shows cutaway views of the complete simulation geometry. The headform is partially transparent in the lower image, showing the positions of all the pads.

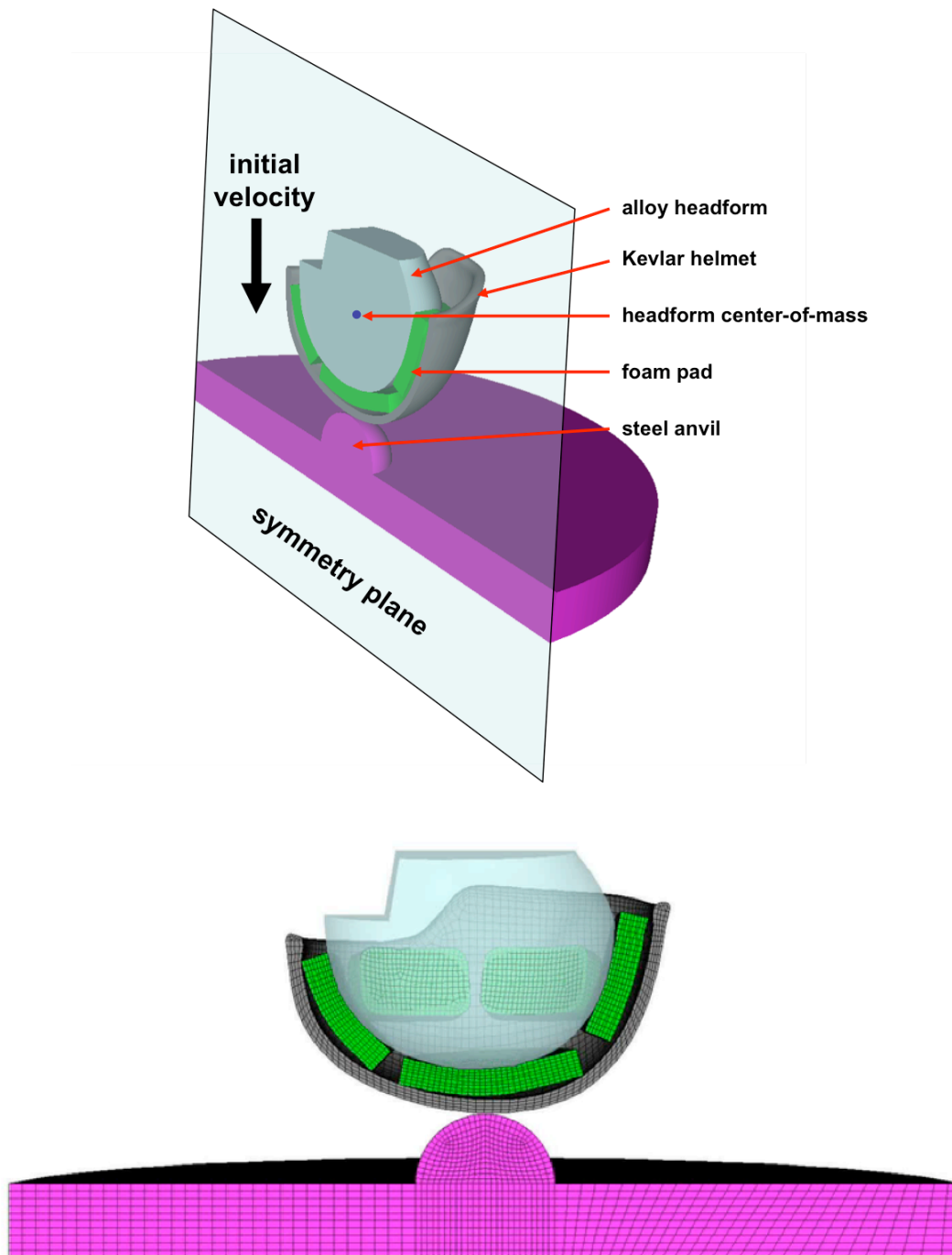


Figure 4 – Crown impact simulation geometry and components

The simulation begins approximately 0.5 ms prior to anvil contact. For simplicity, the pads were positioned approximately in the ACH shell, with some small gaps between them and the helmet shell or headform. At the beginning of the

simulation, the pads quickly conform to the headform and shell geometries under the impact load. Figure 5 shows the geometry at 40 ms for a 10 ft/s impact.

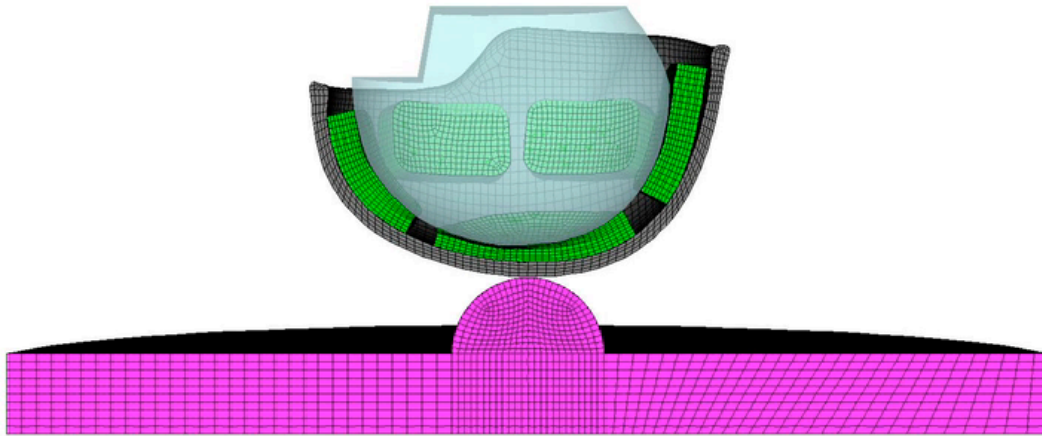


Figure 5 – Simulation geometry at 40 ms for a 10 ft/s impact velocity. The pads have conformed to the shell and are bearing loads.

2.3 Simulation Results

Figure 6 shows comparisons of the simulated and experimental time-dependent helmet rebound velocity (at the headform center-of-mass) for 10 and 14.14 ft/s impact velocities [4]. The experiments and simulations used size 6 Team Wendy pads, with the entire system at room temperature. Two sets of experimental data are shown in the figure to show the typical experimental scatter. Although there are slight differences between the simulations and the experimental data, the agreement of the rebound velocities shows that the overall energy transfer is modeled correctly.

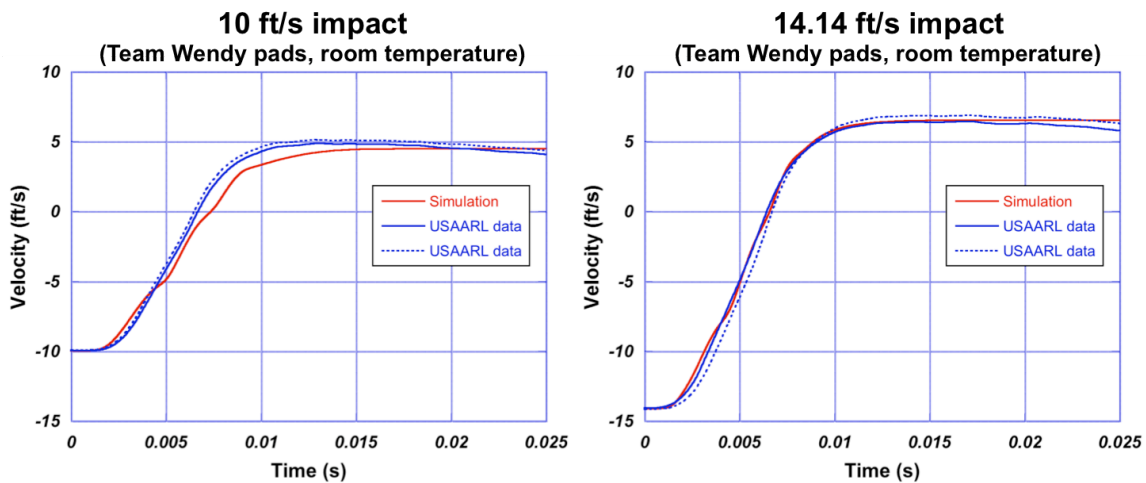


Figure 6 – Simulated helmet rebound velocities are consistent with USAARL data

Figure 7 shows the headform center-of-mass accelerations from the same simulations and experiments. Because accelerometers are very sensitive and prone to noise, acceleration data are typically filtered to extract useful information. Simulation-predicted accelerations are also prone to numerical noise and are generally filtered as well. All the acceleration data in this report were filtered at 1500 Hz, except where noted. Peak (filtered) acceleration is the current metric used by the US Army (and others) for evaluating helmet impact performance. The suitability of peak acceleration and its comparison to another widely used impact metric for injury prediction, called the Head Injury Criterion or HIC [6], is discussed in Appendix D.

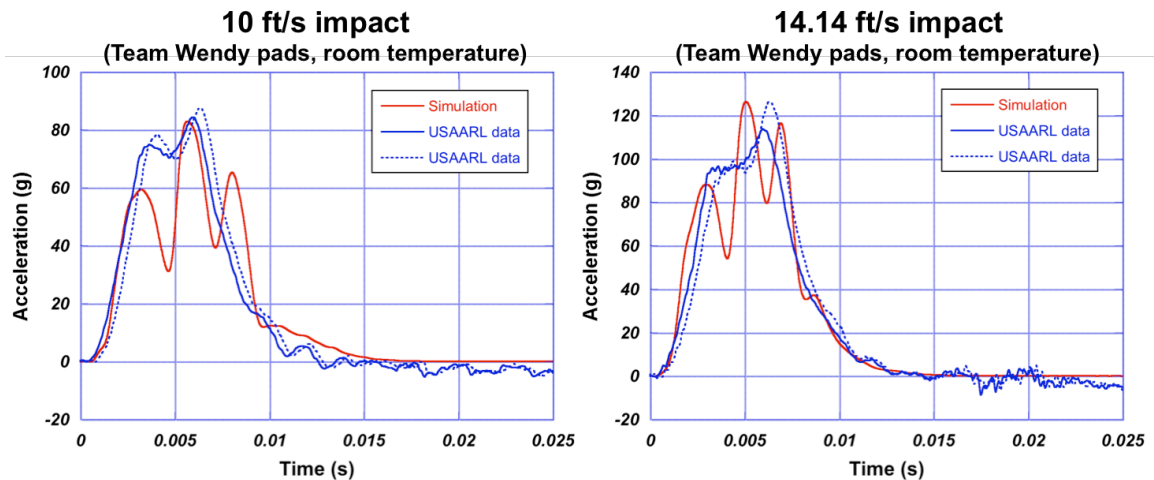


Figure 7 – Simulated acceleration peak values and pulse widths are consistent with USAARL data. Note that the ordinate scales for the two impacts differ.

The peak accelerations from the simulations are within a few percent of the experimental values. The simulated and experimental pulse widths agree very well. The “wiggles” in the simulation may be due to the loose fit of the internal components in the simulation model compared to the “tightly cinched” [7] chinstrap in the experimental setup, or other differences in the constraints on the headform in the experiment versus the simulation. It is also possible that there are damping mechanisms in the experimental configuration, which were not considered in the simulations.

Data for peak acceleration in crown impacts at the same velocities using Oregon Aero pads was also available from USAARL. As an additional check on the simulation methods, the Team Wendy pads in the simulation were replaced with Oregon Aero pads, which are much more compliant (see Appendix B) and the simulations were repeated. Table 1 compares crown impact peak accelerations from the simulations and experimental data [2]. Complete acceleration-time data for the Oregon Aero pads were not available in the USAARL report, so only peak

acceleration data are compared. The simulated results are within the experimental scatter of the data.

Table 1 – Simulations using Oregon Aero pads are also consistent with USAARL peak acceleration data

	Impact velocity (ft/s)	
	10	14.14
Simulation	77g	131g
USAARL Data	77g ± 5g	145g ± 25g

The simulations are very useful for visualizing details that are difficult to access experimentally: for example, impact-induced permanent deformation of the helmet. The Kevlar™ material model in the simulation included plasticity. Figure 8 shows that, for the 14.14 ft/s impact, the simulation predicts a small amount of plastic strain (maximum of 3%) in the region where the helmet contacts the anvil.

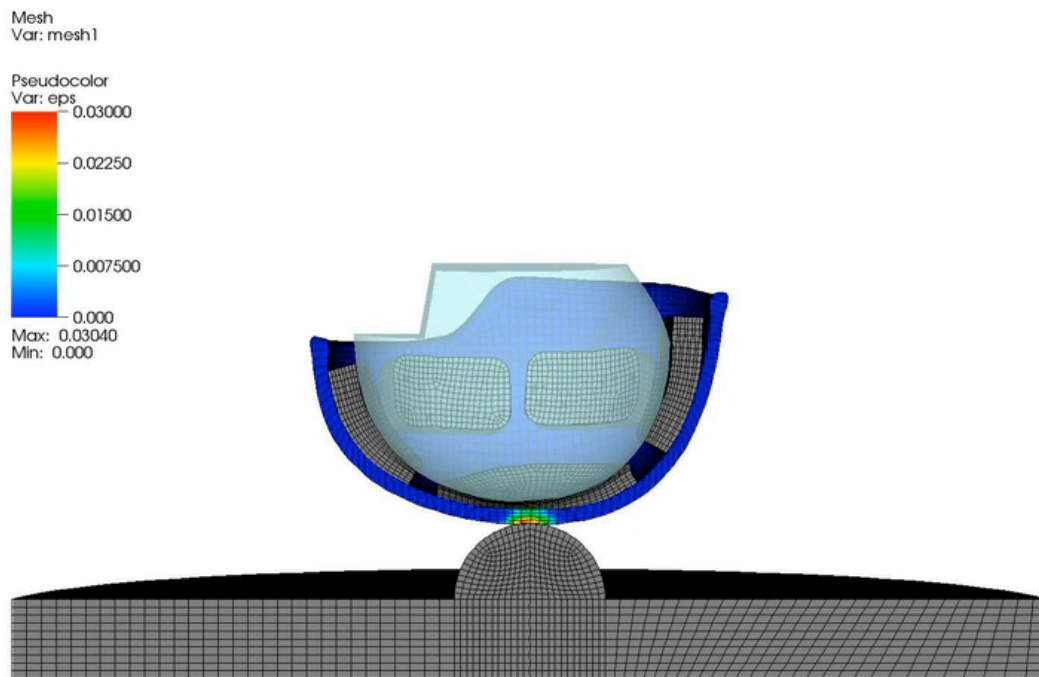


Figure 8 – Simulations allow visualization of details that are difficult to access experimentally. Plastic strain in the helmet is shown ~7.5 ms after impact for a 14.14 ft/s impact velocity.

The results of this simulation suggest that a subsequent impact might yield different peak accelerations, as a result of the permanent plastic deformations in the helmet shell created during the first impact. Plasticity is a damping mechanism, so we would expect larger peak accelerations in a subsequent impact at 14.14 f/s, which is consistent with experimental data (see Fig. 12 in [2]).

The simulations also allow parameter sensitivities that are not amenable to experimental investigation to be explored numerically: for example, the effects of helmet plasticity and/or the airtight covering/coating on the foam pads. Design insights can be gained from understanding these sensitivities. Figure 9 builds on the results shown in Figure 8, in which we show how peak accelerations for the original 14.14 ft/s impact (Team Wendy pads, room temperature) are modified when the Kevlar™ is constrained to respond only elastically, and then in addition when the airtight covering around the foam is removed. The figure shows that the peak accelerations are very sensitive to these parameter changes. The solid black line shows the original simulation. The peak acceleration increases when the helmet is constrained to respond elastically, which confirms the conclusion in the previous paragraph and implies that a helmet shell that does not yield as much will cause greater peak accelerations for this particular impact scenario. Removal of the airtight covering (dashed red line) increases the peak acceleration by almost another 100 g, implying that, for this particular impact scenario, the effects of the plastic covering are significant and beneficial.

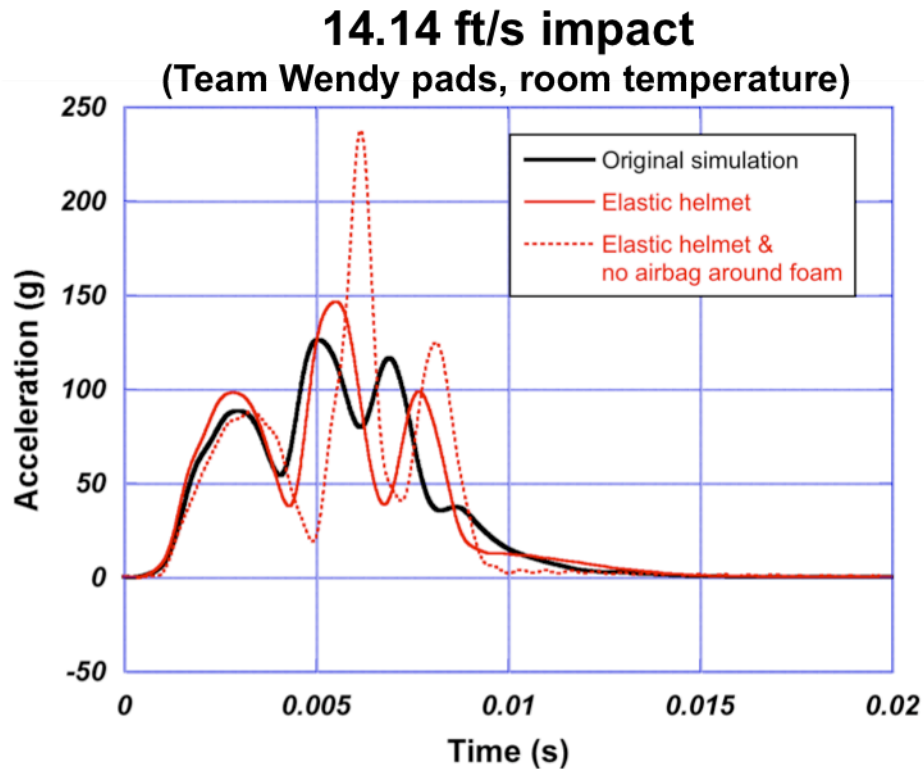


Figure 9 – Parameter sensitivities that are not amenable to experimental study are amenable to numerical study

The comparisons between the simulations and the experimental data for both the Team Wendy and Oregon Aero pads demonstrate that the simulation method is robust and accurate and can be used reliably to address the tasks in this project. In addition, the figures show that simulation is a powerful tool for exploring “what if” scenarios and can aid the design, testing, and optimization of equipment.

3. Cylinder Impact Simulations

3.1 Description of Simulations

One of the main objectives of the study is to determine whether the pads used in football helmets would outperform the pads used in the U.S. Army systems in combat-relevant impact scenarios. However, it is not possible to simply simulate what would happen if football pads were placed inside an ACH, because the football helmet pads do not physically fit in an ACH.

Football helmet shells are much larger and cover more of the head than the ACH, and their pads are generally nearly double the thickness of the pads used in the ACH. In addition, the size, shape, and distribution of the pads within the helmet differ between the football and the Army systems. These differences are shown in Figure 10.

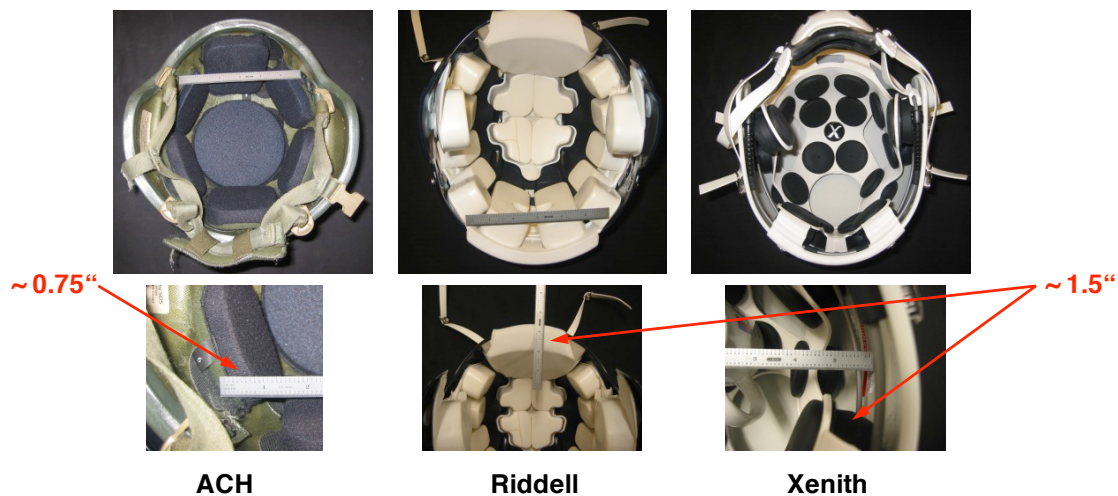


Figure 10 – Differences in helmet pad size and shape between Army and football systems

In order to compare the performance of incompatible material systems, a simplified geometry was developed, shown in Figure 11. This geometry consists of a cylindrical impactor hitting a circular pad sitting on a rigid surface. An initial velocity is imparted to the impactor. The velocity and acceleration history of a tracer particle at the center of the cylinder is tracked, and the Head Injury Criterion [HIC] associated with this acceleration history is used to compare the performance of the different pad materials. Refer to Appendix D for a description of the HIC.

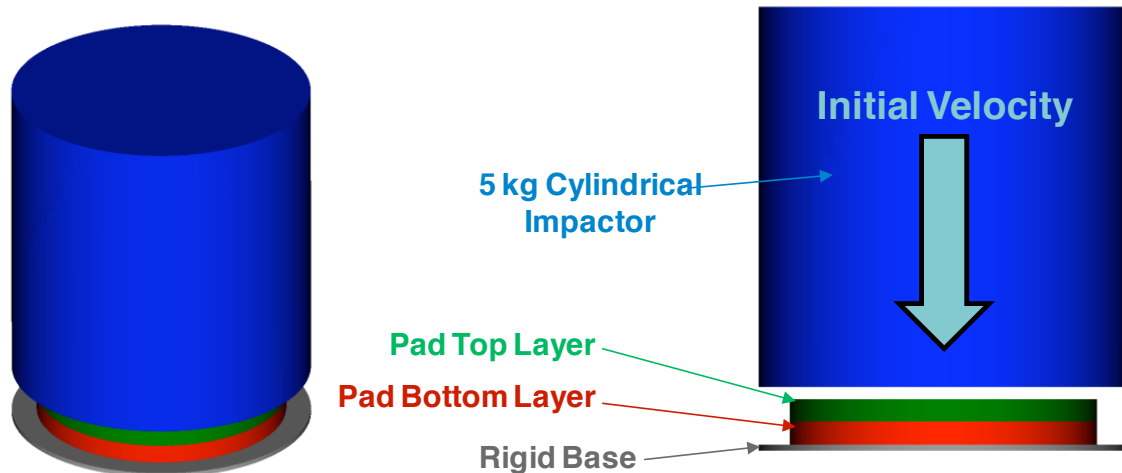


Figure 11 – Simplified cylinder impact geometry

The impactor is made of magnesium alloy, like the experimental headforms used by USAARL, because the density of the alloy is similar to the average density of a human head. It weighs 5 kg, which is comparable to an adult human head, and has a diameter 10% greater than the pad so that edge effects do not affect the simulation. Impact velocities range from 5 to 20 ft/s, which is the range of impact velocities of interest in nonlethal military impact scenarios.

In most simulations, the pad is nominally 0.75 inches thick and 5 inches in diameter, which is equivalent to a #6 Team Wendy ACH crown pad, although different studies with different pad thicknesses or areas were conducted. When a bilayer foam (like the Riddell) was used, but simulated with a thickness different from an actual pad, the two simulated foams were used in the same proportion as the actual system.

Finally, for the Team Wendy and Oregon Aero pads, which have an air-tight covering or a coating, the effects of the trapped air was included by adding additional stiffness to the pad system, which is described in Appendix C .

3.2 Comparison between Cylinder Impact and Full Pad Simulations

The simplified cylindrical impact geometry discussed in the Section 3.1 allows the impact mitigation of the different pad materials to be compared to one another directly, isolating the material response and eliminating the complexities of the full helmet system. These complexities include obliquity of impact effects on some of the pads, the deformation of the helmet shell, and load sharing between different pads with different positions and geometries. The simplified simulations have the added benefit requiring significantly less computational time to run than

the full helmet simulations, allowing large numbers of sensitivity runs to be conducted rapidly.

Note that these simulations are intended to compare the impact response of different materials, not the injury mitigation capability of complete systems. Just because one material mitigates relevant impacts better than another does not necessarily mean that the corresponding pad system is necessarily more effective at preventing injury, since system-level effects not captured by the cylinder impact simulations may affect the response as well.

This is evident in Figure 12, which compares acceleration traces associated with USAARL crown impacts on helmets with Team Wendy pads, full helmet simulations of those crown impacts described in Section 2, and cylinder impact simulations against a typical #6 Team Wendy crown pad, at two different impact speeds. At both speeds, the full helmet simulations predict the experimental data reasonably well, especially with regard to peak acceleration and acceleration duration. Some additional oscillations appear in the full helmet simulation response due to complexities of the system, as described in Section 2.3.

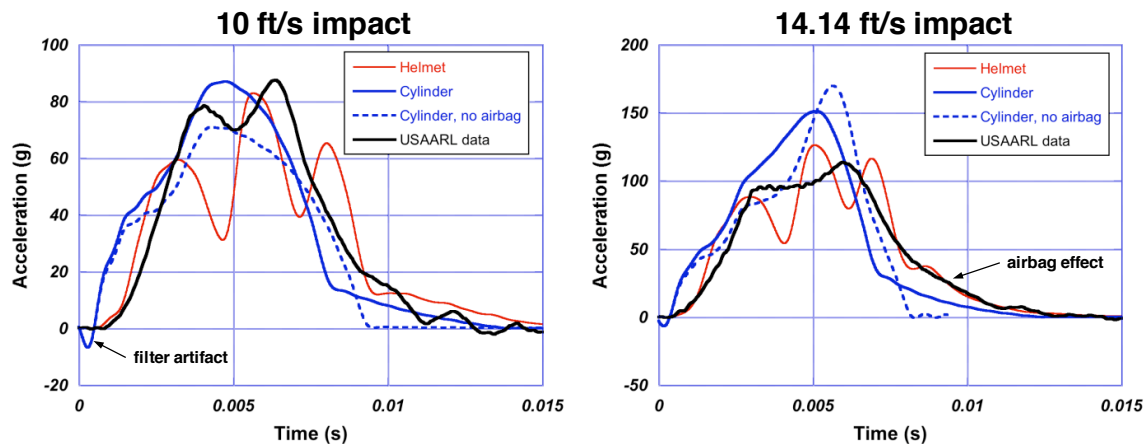


Figure 12 – Comparison of the experiment (black), full helmet simulations (red), and cylinder impact simulations (blue) for impacts against Team Wendy pads at two different speeds

At 10 ft/s, the cylinder impact simulations produce similar acceleration histories as both the full helmet simulations and the experiment. At 14 ft/s, the cylinder impact simulations tend to overpredict the peak acceleration and underpredict the acceleration duration. It is hypothesized that this is due to system-level effects. At lower speeds, the bulk of the impact energy is likely absorbed by the crown pad, which is captured well by the cylinder impact simulation. At higher speeds, pad deformations are more significant and other pads (and possibly the helmet shell itself) likely absorb some of the impact energy. Because the complete helmet system spreads the impact out over a larger area, the foam pads are not

compressed as far as the simple cylinder impact simulation suggests, reducing the peak acceleration and increasing the duration of the impact.

Consequently, the cylinder impact simulations are useful for fairly comparing the impact absorption capability of different foams, but cannot be used directly to predict injury.

3.3 Results of Cylinder Impact Analyses

3.3.1 General Response of Foams to Impacts

Under the simplified impact conditions of the cylinder impact analyses, the foam materials all displayed a similar response, represented schematically in Figure 13. Force is plotted as a function of compression; the area under the curve gives the energy absorbed or dissipated by the foam. After a brief elastic response, the foams begin to crush and the force reaches a plateau. If the foams become densified before the impact energy is dissipated, the force increases dramatically.

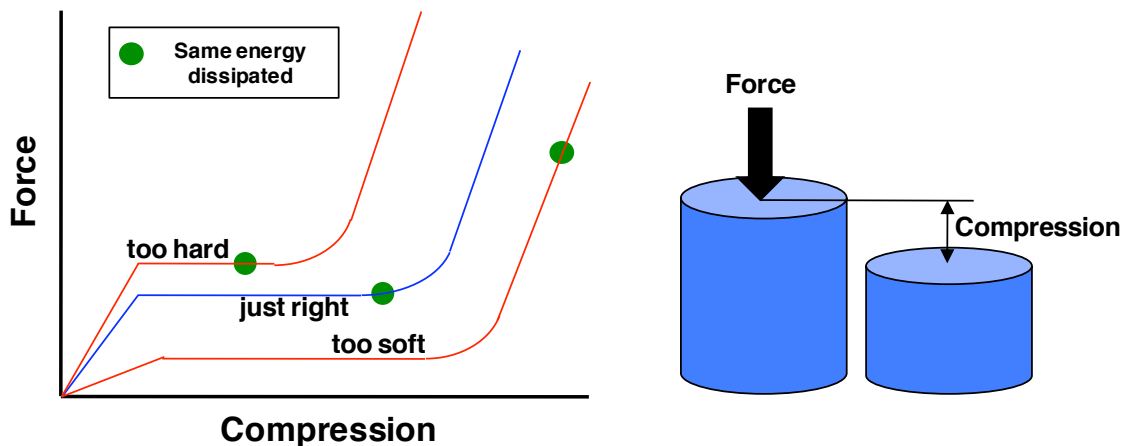


Figure 13 – General response of a foam to compression during an impact

Since the peak acceleration is directly proportional to the force, this general response demonstrates why a particular foam is suitable for protecting against impacts of a given energy (*i.e.* a given impact speed and mass of object). A very hard foam with a high crush plateau will dissipate all the impact energy without ever densifying. However, it does so by applying a larger force (and hence a greater acceleration) than is necessary. A softer foam that is “just right” uses the entire crush plateau to dissipate the impact energy, and hence does so at a lower force (and lower acceleration). However, if a foam is too soft for a given amount of impact energy, it densifies and “bottoms out”, and the peak force (and hence peak acceleration) grows very large. A single foam will be optimal for only one specific amount of impact energy.

Use of a multilayer foam can partially address this issue. By mixing a soft foam with a harder foam, a wider range of impact energies can be addressed. The softer foam will generally absorb as much energy as it can before the harder foam begins to deform significantly. However, once the softer foam densifies, the remaining energy will be absorbed by the compaction of the harder foam.

3.3.2 Effects of Foam Material

Figure 14 compares the cylindrical impact simulation results for the three systems composed of bilayer foam pads (Team Wendy, Oregon Aero, and Riddell) over a range of velocities from 5 to 15 ft/s. The monolayer d30 foam was excluded from our comparisons, due to its extreme stiffness (see Appendix B). The x-axis is the relative kinetic energy of the impactor normalized to a 10 ft/s impact. The y-axis is the HIC associated with the acceleration history of the impact (refer to Appendix D for a description of the HIC). All simulations used the same pad geometry — a #6 ACH crown pad (0.75 inches thick and a 5 inch diameter, with a total area of 19.63 in²). The fractions of soft and hard foam in each simulation were the same as in the actual pad systems (50%-50% for the Team Wendy and Oregon Aero, and 29%-71% for the Riddell). The Team Wendy and Oregon Aero pads were simulated with the effects of their airtight covering/coating intact, *i.e.* additional stiffness was added to take the effects of the trapped air into account as described in Appendix C. All simulations were conducted assuming the room temperature response of the pads.

All simulations employed a 5 kg impacting cylinder.

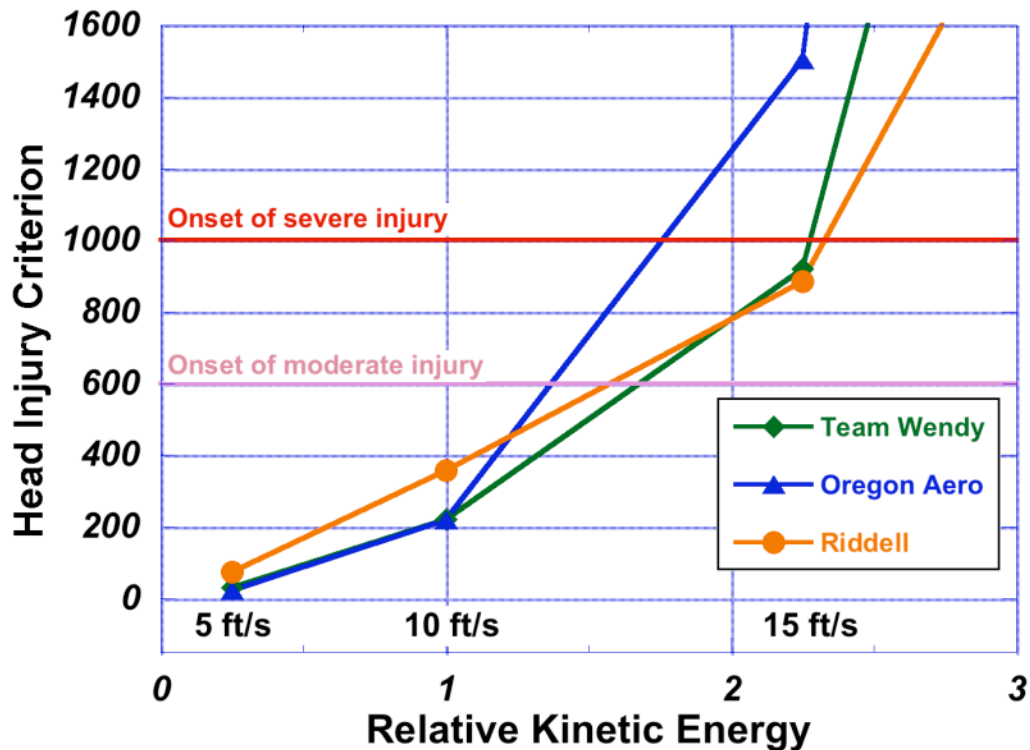


Figure 14 – HIC as a function of relative kinetic energy for cylinder impact simulations of three different pad systems with identical geometries and a 0.75 inch thickness

The Riddell system is the hardest of the three pad systems, while the Oregon Aero is the softest. At low speeds (10 ft/s or less), the Team Wendy and Oregon Aero pads produce an almost identical HIC, while the Riddell pad produces a slightly larger HIC (although still small relative to injury metrics). As the impact velocity is increased to 15 ft/s, the Oregon Aero pad reaches a point when both foams completely densify and the peak acceleration (and hence the HIC) increase greatly relative to the other two pad systems. At 15 ft/s the Team Wendy pad is just starting to densify, whereas the harder Riddell pad is still resisting the impact in the plateau region of its harder foam. As a result, the Team Wendy pad produces a similar HIC to the Riddell pad. Both pads are approaching the limit of their impact absorption capabilities.

At 20 ft/s, even the Riddell pad system has started to densify, and all three pads have exceeded their effective impact absorption capabilities. The Oregon Aero pad produces the highest HIC in this case, followed by the Team Wendy pad and then the Riddell pad.

For identical pad geometries, the Oregon Aero pads and the Riddell pads provide no apparent benefit over the Team Wendy foams currently used in the ACH for

militarily relevant impact scenarios. However, it should be noted that this comparison is not necessarily representative of the actual pad employment strategies since it compares identically sized pads. The Riddell pads that protect against crown impacts in the Riddell football helmet have less area than an ACH crown pad. Simulations examining the effects of pad area are described in Section 3.3.6.

Note that while these results indicate that a single 0.75 inch thick crown pad likely cannot protect against injuries above 15 ft/s, an entire helmet system that spreads the impact across multiple pads and includes the effect of the helmet shell could be more effective. As stated above, the cylinder impact simulations are useful for comparing one material to another but do not necessarily predict the likelihood of injury in an impact involving a full helmet system.

3.3.3 Effects of Air-Tight Covering/Coating

Both the Team Wendy and the Oregon Aero pads are surrounded by an airtight covering/coating that affects their material response. The effects of the covering/coating are included in the model by adding additional stiffness to the pad, as described in Appendix C. Cylinder impact studies were conducted on the pads with and without this additional stiffness in order to determine how the pad's impact absorption capabilities would be affected if the covering was punctured or removed.

Note that, although the Riddell system also has an airtight covering for the pads, compression tests indicated that this covering does not affect the pad response, whether it is inflated or not. This is presumably due to the relief channels between adjacent pads that allow air to flow from one pad to its neighbors.

Figure 15 compares the cylinder impact simulation results for the Team Wendy and Oregon Aero pads with and without their airtight covering/coating over a range of velocities from 5 to 15 ft/s. The x-axis is the relative kinetic energy of the impactor normalized to a 10 ft/s impact. The y-axis is the HIC associated with the acceleration history of the impactor (refer to Appendix D for a description of the HIC). All simulations used the same pad geometry— a #6 ACH crown pad (0.75 inches thick and a 5 inch diameter, with a total area of 19.63 in²). The fractions of soft and hard foam in each simulation were the same as in the actual pad systems (50%-50%). All simulations were conducted assuming the room temperature response of the pads.

All simulations employed a 5 kg impacting cylinder.

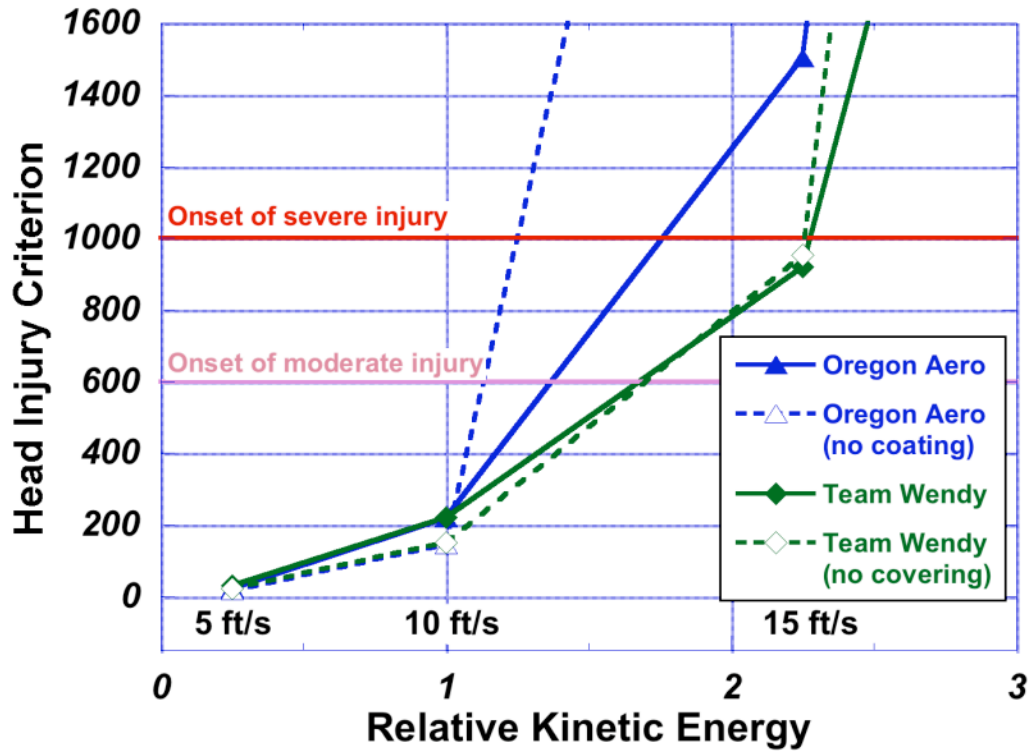


Figure 15 – Effects of airtight covering on Team Wendy and Oregon Aero pads in cylinder impact simulations

The pad covering/coating traps air as it escapes from the pad during compression. This adds additional stiffness to the system, effectively making a pad harder, and also making the entire system act more elastically when unloaded (increasing the duration of the acceleration). At low impact speeds, removing the coating eliminates both these effects, rendering the pads softer and less elastic, which produces a slightly lower HIC for both pads.

However, because the uncovered pads are effectively softer, they densify under smaller impact energies. Therefore, at higher impact speeds, the uncovered pads produce a larger HIC. This is especially apparent for the Oregon Aero pads, which show a dramatic increase in HIC above 10 ft/s when the pads are uncoated, compared to when the pad coating is intact. The difference in the Team Wendy response is less dramatic: at 15 ft/s, the uncovered Team Wendy pads produce only a slightly higher HIC than the covered pads.

The difference in the dependence on the trapped air between the two pad systems may be in part because the Oregon Aero foams are softer than their Team Wendy counterparts, so the stiffness of the air trapped inside is a more significant part of the total pad system response than it is for the Team Wendy pads. It also may be related to the fact that the airtight coating on the Oregon

Aero pads is bonded to the exterior surfaces of the foams, whereas the Team Wendy pads are covered by an unattached plastic bag. As a result, the air response is more strongly coupled to the pad in the Oregon Aero system than in the Team Wendy system, so removing the air response produces a more dramatic change.

For both systems, the airtight covering/coating is probably beneficial. Removing the covering/coating has some slight benefit in low-velocity impact regimes where injury is unlikely anyway, but is detrimental to the pad response in higher-velocity impact regimes where injury is more likely.

3.3.4 Effects of Pad Thickness

The amount of energy a pad can absorb before it densifies is strongly dependent on its thickness. Thicker pads employ a greater “stopping distance” and hence can dissipate a given amount of energy with less force (and hence a lower peak acceleration, HIC, and chance of injury). The pad thickness is governed by the clearance gap required between the head and the helmet.

Figure 16 compares the cylinder impact simulation results for Team Wendy pads of different thicknesses ranging from 0.6 inches up to 1.5 inches, over a range of velocities from 5 to 15 ft/s. The x-axis is the relative kinetic energy of the impactor normalized to a 10 ft/s impact. The y-axis is the HIC associated with the acceleration history of the impactor (refer to Appendix D for a description of the HIC). All simulations used the same pad diameter and area (5 inch diameter and a total area of 19.63 in²). The fractions of soft and hard foam in each simulation were the same as in the actual #6 pad system (50%-50%). All simulations were conducted assuming the room temperature response of the pads.

All simulations employed a 5 kg impacting cylinder.

For reference, note that the #6 ACH crown pad has a thickness of 0.75 inches, and the #8 ACH crown pad has a thickness of approximately 1.0 inch.

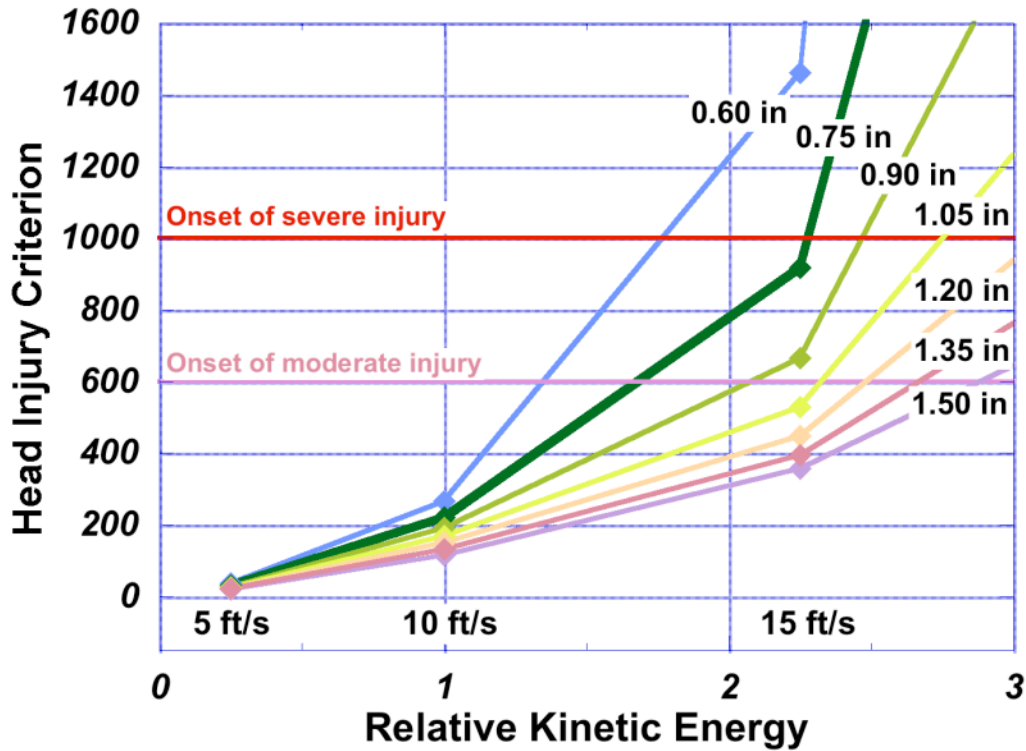


Figure 16 – Effects of pad thickness for Team Wendy pads in cylinder impact simulations

At every impact velocity, a thicker pad produces a lower HIC, although the effect is most significant at larger velocities. The effect can be quite significant; for example, at 15 ft/s, increasing the pad thickness by 0.15" from 0.75" to 0.90" reduces the HIC from a high value of 917 to a more moderate value of 665, and increasing by another 0.15" to 1.05" reduces it to a much lower value of 528.

For a given impact energy, there is a limit to the benefit imparted by thickening the pads. At 10 ft/s, little benefit is attained with pads thicker than 0.75". At 15 ft/s, little benefit is attained with pads thicker than 1.20". This is likely because the main benefit of a thicker pad is that it absorbs more energy before it densifies. When a pad is thick enough to avoid densification at a given energy, additional thickness reduces the HIC by only small amounts.

The dependence of the HIC on thickness suggests a commercial off-the-shelf solution for mitigating impact-related traumatic brain injury to soldiers. By wearing helmet shells that are at least one size larger and have thicker pads, the injuries from impacts, especially severe impacts, could be reduced significantly.

3.3.5 Comparison of the Xenith to Other Pad Systems

The Xenith pad system is not a bilayer foam; it is a complex air-filled structure designed to elastically buckle at a given load and expel air at a controlled rate. (It includes a small amount of foam against the head for fit and comfort, but this foam has little effect on the response of the pad system). It is approximately 1 inch in diameter and 1.5 inches thick. The pad system is engineered to produce a response that is similar to that of a bilayer foam. However, because it is an engineered structure, its response does not scale to the 0.75 inch thickness of a #6 ACH crown pad. If a Xenith-type system were to be employed in a ACH, either the shell would have to be modified to accommodate the Xenith pad's 1.5 inch thickness, or the pad would have to be re-engineered to produce an appropriate compression response with a 0.75 inch thickness.

On the other hand, because the other three pad systems are bilayer foams, they can be scaled to the larger thickness of the Xenith pad. This allows the response of the Xenith pad system to be compared fairly to the response of the other three pad systems.

The Xenith pad system can be modeled as a bilayer foam as described in Appendix B.3.4. Although an actual Xenith pad cannot be easily scaled up to the 5 inch diameter of an ACH crown pad, the cylinder impact simulations of a single 5" diameter pad with Xenith-like behavior can be thought of as being equivalent to some number of Xenith pads with a total combined area of 19.63 in² acting side by side.

Figure 17 compares the cylinder impact simulation results for the Team Wendy, Oregon Aero, and Riddell bilayer foam pad systems to the Xenith pad system over a range of velocities from 5 to 20 ft/s. The x-axis is the relative kinetic energy of the impactor normalized to a 10 ft/s impact. The y-axis is the HIC associated with the acceleration history of the impact (refer to Appendix D for a description of the HIC). All simulations used the same pad geometry—1.50 inches thick and a 5 inch diameter (19.63 in² area). The fractions of soft and hard foam in the three foam pads systems were the same as in the actual pad systems (50%-50% for the Team Wendy and Oregon Aero, and 29%-71% for the Riddell). The Team Wendy and Oregon Aero pads were simulated with the effects of their airtight covering/coating intact, *i.e.* additional stiffness was added to take the effects of the trapped air into account, as described in Appendix C. All simulations were conducted assuming the room temperature response of the pads.

All simulations employed a 5 kg impacting cylinder.

Note that because the pad systems compared in Figure 17 have a 1.50 inch thickness, the HIC values are lower at all velocities than for the same systems in Figure 14, which had only a 0.75 inch thickness.

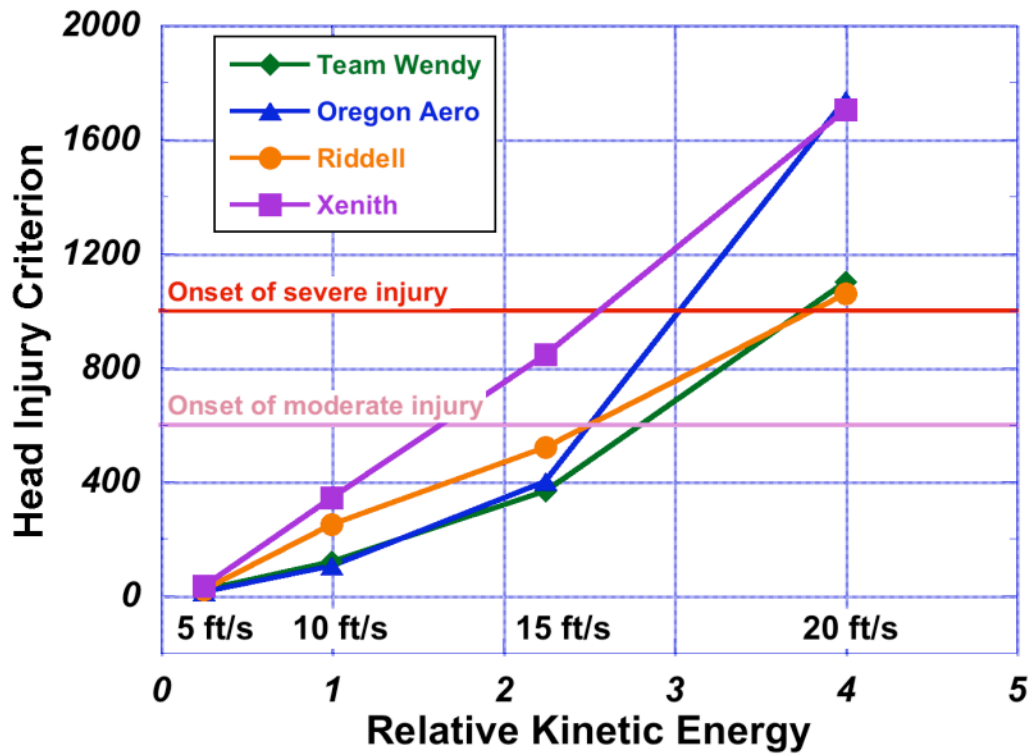


Figure 17 – Cylinder impact simulations of four different pad systems with identical geometries (1.5 inch thick)

For the three foam pad systems, the results are similar to those shown in Figure 14, although with lower HIC values at all velocities. The Team Wendy and Oregon Aero foams are the softest and have the lowest HIC values at low speeds. The soft Oregon Aero pads begin to densify at impacts of about 15 ft/s, while the harder Team Wendy pads begin to densify at somewhat higher speeds. Note that because of the increased thickness, densification occurs at a higher speeds for both pads relative to the results in Figure 14. The Riddell pad is harder and produces a higher HIC at low speeds, but never densifies and produces the lowest HIC at 20 ft/s.

For the same 1.5 inch thickness and 19.63 in² total pad area, the response of the Xenith pads is significantly stiffer (*i.e.* the pads are harder) than any of the foam pad systems. Consequently, they produce a higher HIC at every impact speed, and like the Riddell pad, never densify (*i.e.* buckle to the point where their inner cavities completely collapse).

As was the case for the 0.75 inch thick pads, for identically sized pads, the Oregon Aero pads and the football pads (Riddell and Xenith) do not provide any apparent benefit over the Team Wendy pads in a militarily-relevant impact scenario.

However, it is not representative of actual pad employment strategies to compare pads of identical areas. In a football helmet, Riddell pads protecting against crown impacts have a smaller area than an ACH crown pad. No Xenith pads have an area of 19.63 in². In a Xenith-padded football helmet, the crown of the head contacts only two to four Xenith pads, each with an area of 3.14 in². This is also characteristic of other parts of the head—generally, only two to four Xenith pads absorb the energy of any given impact. It is more representative to compare Riddell and Xenith pads with a reduced area, as is described in Section 3.3.6.

3.3.6 Effects of Pad Area

Figure 18 compares the cylinder impact simulation results for a 1.5 inch thick Team Wendy crown pad (with an area of 19.63 in²), 1.50 inch thick Riddell pads with areas of 19.63 in² and 9.82 in², and 1.5 inch thick pads with Xenith behavior and areas of 12.56 in² (corresponding to four Xenith pads) and 6.28 in² (corresponding to two Xenith pads). The x-axis is the relative kinetic energy of the impactor normalized to a 10 ft/s impact. The y-axis is the HIC associated with the acceleration history of the impact (refer to Appendix D for a description of the HIC). The fractions of soft and hard foam in the two foam pad systems were the same as in the actual pad systems (50%-50% for the Team Wendy and 29%-71% for the Riddell). The Team Wendy pads were simulated with the effects of their airtight covering intact, *i.e.* additional stiffness was added to take the effects of the trapped air into account, as described in Appendix C. All simulations were conducted assuming the room temperature response of the pads.

All simulations employed a 5 kg impacting cylinder.

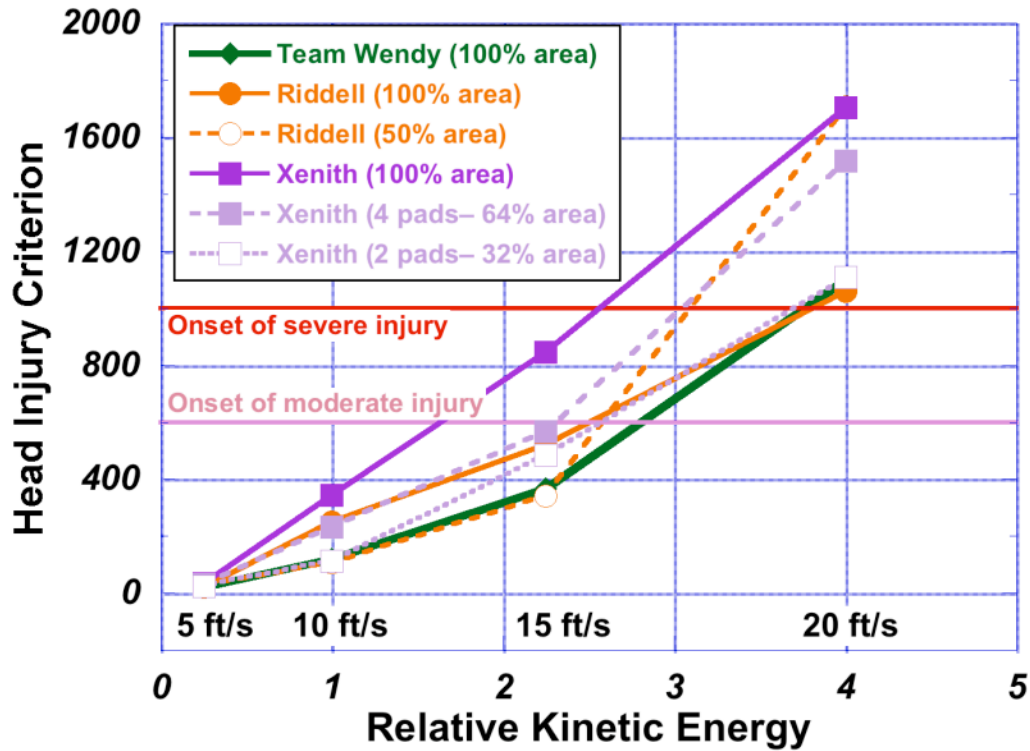


Figure 18 – Effects of pad area in cylinder impact tests, for a 1.5 inch pad thickness

Reducing a pad's area effectively makes it softer. When the Riddell pad's area is reduced by 50% (roughly comparable to the area that actually supports the crown of the head in a football helmet), its response at lower impact speeds is comparable to the Team Wendy pad system. However, the reduced area Riddell pad densifies above 15 ft/s and its HIC value at 20 ft/s is significantly higher than the Team Wendy pad or the full area Riddell pad.

The reduced area Xenith pads also produce a lower HIC at low speeds than the full area Xenith pad. Two 1" diameter Xenith pads are comparable to the 5" diameter Team Wendy pad at 5 and 10 ft/s. They produce a slightly higher HIC at 15 ft/s, but never densify, so that at 20 ft/s they are comparable to the Team Wendy, which is densifying.

When pad areas are reduced, the NFL systems produce HIC values that are comparable to the Team Wendy system at low speeds (and, in the case of the Xenith pad, at high speeds as well). However, at no speed do the NFL systems exceed the performance of the Team Wendy system. The NFL pad systems provide no apparent benefit over the Team Wendy system in militarily relevant impact scenarios.

This does not imply that the Team Wendy pad system would necessarily be better than the NFL systems in football-relevant impact scenarios. In combat, a soldier is likely to be knocked to the ground or against an object or suffer a glancing blow to the head by debris or shrapnel. In such impacts, it is appropriate to consider only the mass of the head when determining the impacting mass that the pads must absorb. However, in many football-relevant impact scenarios, the entire body mass of the player is driving the head into another object, and hence the impact energy that the pads must absorb may be greater. This could explain why the NFL pads tend to be both thicker and harder than the pads developed for the Army—they are designed for a different type of impact.

4. Conclusions

We successfully used computational simulations to study how different foam pad suspension systems mitigate head impacts. We considered the Team Wendy foam pads currently used in the ACH, the Oregon Aero foam pads formerly used in the ACH, air-filled Riddell foam pads used in football helmets, and Xenith pads used in football helmets. For each of these systems, we performed experiments that allowed us to characterize the material response of different foams and of the complete pad system, and fit material properties to these experiments so that available foam material models would capture the foam response in the relevant loading regime.

We used CT scans of the helmet shell to develop computational models of the helmet with a high amount of geometric fidelity. Then, by combining the material models of the foam and the geometric model of the helmet shell, we were able to computationally recreate a series of crown impact experiments conducted at USAARL, and showed that the simulations could capture the essential features of the experimental data (peak acceleration, impact duration, rebound velocity, and impact severity as measured by the HIC). This gave us confidence in the validity of our computational approach, and also provided insight into the different physical mechanisms by which impact energy is absorbed or dissipated by the helmet and its pads.

We then developed a simplified simulation geometry for isolating the effects of the foam material from other effects (*e.g.* interactions between pads and deformations of the helmet shell). This was necessary because the football pads as manufactured are not geometrically compatible with the ACH shell, so a simplified geometry was necessary to perform a fair comparison of the performance of the different materials. In this geometry, a cylinder with a mass comparable to a human head was impacted against a circular pad comparable in size and geometry to an ACH crown pad. We conducted a large number of sensitivity studies examining how the impact response depended on foam material, pad thickness, pad area, trapped air, and various other parameters.

Our key findings from these studies are:

- The performance of a pad depends on the range of impact velocities. At lower impact velocity, softer pads perform better. At higher impact velocity, harder pads perform better.
- Thicker pads perform better at all velocities, but especially at high velocities.

- For comparable thicknesses, neither the NFL systems nor the Oregon Aero pads outperform the Team Wendy pads currently used in the ACH system in militarily-relevant impact scenarios (impact speeds less than 20 ft/s).

The second finding suggests a commercial off-the-shelf solution for mitigating impact-related traumatic brain injury to soldiers. By simply using helmet shells that are at least one size larger with thicker pads, the injuries from impacts, especially severe impacts, may be reduced significantly.

We believe that an important outcome of our work is the demonstration of how numerical modeling, simulation, and analysis can complement experimental tests to improve the final product and yield overall cost savings during product design, development, and testing. Just because no system in the current study outperforms the Team Wendy pads does not mean that an improved system could not be devised. However, we note that since the helmet must protect against ballistic attacks, impacts over a wide range of speeds, and blast loadings, a single best design for the suspension system may not exist and compromises may have to be made to provide a system that offers a reasonable amount of protection over the probable range of threats.

5. Acknowledgments

We thank LLNL staff members B. Cracchiola for loaning us his ACH helmet, D. Urabe for performing the compression tests on the manufacturer supplied pads and component foams, and W. Brown for CT scanning the ACH helmet and post-processing the files. We also thank N. Kraemer (Riddell), S. Reynolds (Xenith), R. Szalkowski (Team Wendy) and T. Erickson (Oregon Aero), for supplying pad and foam samples used in this study.

6. References

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Appendix A Component Geometry

A.1 ACH Helmet Shell

The meshed geometry for the ACH helmet shell was developed from a Size Large ACH shell, manufactured by SDS (part number 8470-01-523-0071), on loan from B. Cracchiola (LLNL). This shell was scanned using X-ray computed tomography [CT] and a 3D representation of the geometry was developed. This 3D model was then smoothed and meshed.

A.1.1 CT Scan

The CT scan was performed using a 450 kV X-ray that took 720 images over 360° (an image every 0.5°). The setup is shown in Figure 19.

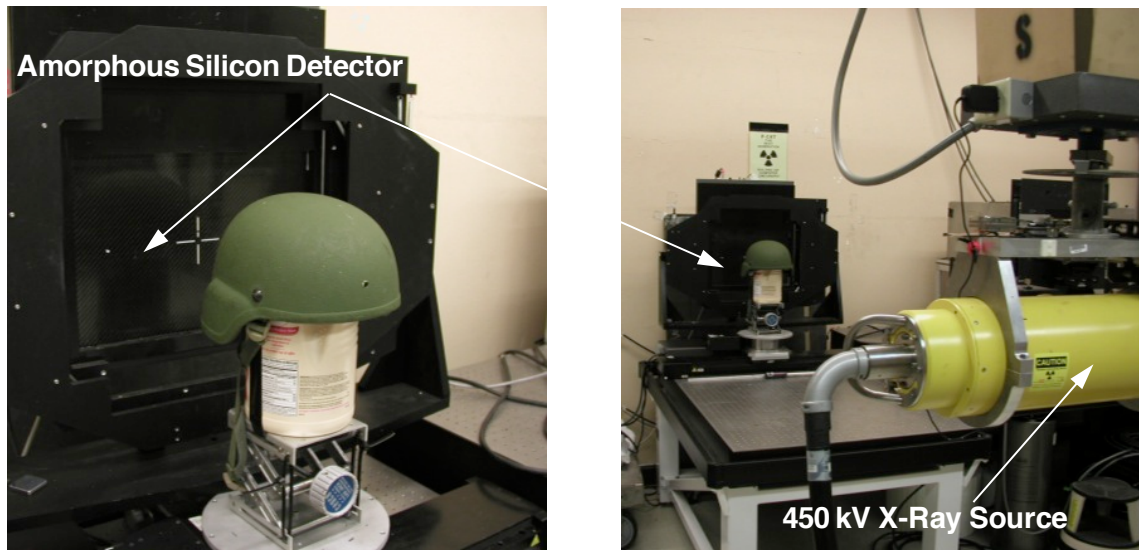


Figure 19 - X-ray tomography setup with ACH helmet shell

Using CT techniques, these images were reconstructed into a 3D image with dimensions of 2,133 x 1,650 x 1,000 voxels, with a resolution of 169 μm per voxel. A typical “slice” of the 3D CT image, taken normal to the forward direction is shown in Figure 20. The lightest region is the Kevlar™ shell, while the other visible regions are the pads and the stand that supported the helmet during the X-ray process.

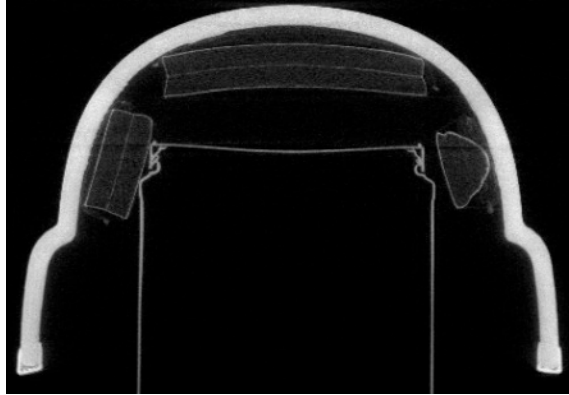


Figure 20 - CT image of ACH shell (slice is normal to the forward direction)

The CT images were thresholded and segmented so that a 3D representation of the helmet shell could be generated. For efficiency, this 3D representation was down-sampled. The down-sampled 3D model of the helmet is shown in Figure 21. The circular structures visible on the inside surface are the Velcro™ pads used to affix the pads to the shell.

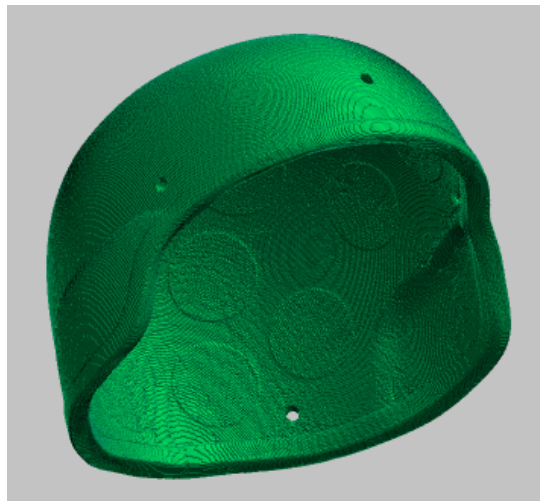


Figure 21 - 3D model of ACH shell

A.1.2 Mesh Development

The 3D model of the helmet shell generated from the CT scanning process is not directly usable in finite element analysis codes. While every voxel could be rendered as an individual element, this approach would yield a finite element mesh that is excessively large and that also has an unrealistic surface topology. Namely, a smooth, curving surface will be represented as a series of cubic facets

resembling blocks or stair steps. Down sampling the 3D model to use bigger voxels alleviates the size issue but exacerbates the surface topology problem.

Instead, the 3D model was smoothed and then meshed with conforming hexahedral elements. Using VisIt, a visualization and image analysis tool developed at LLNL, a contour map of the helmet was generated from the 3D model. These contours were then smoothed. Next, using Cubit, a 3D mesh generation tool developed at Sandia National Laboratory, the smoothed contours were reconstructed into a smooth-surfaced meshable object. This object was then meshed using Cubit's paving and sweeping algorithms. The resulting hexahedral helmet mesh is shown in Figure 22.

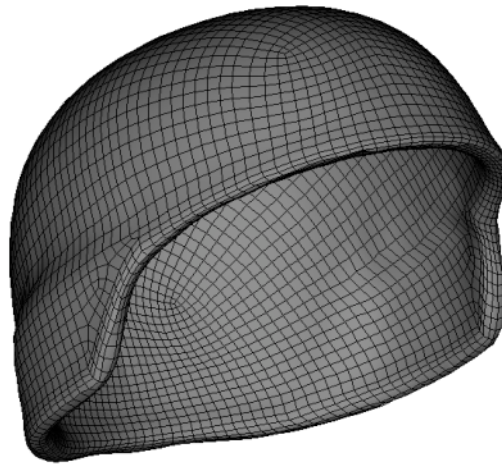


Figure 22 - Hexahedral helmet mesh

A.2 Headform

The headforms used in USAARL's experiments ([2],[4]) were Cadex EN960 Magnesium K1A half headforms. Cadex provides complete engineering drawings of their full EN960 headform on their website [10], but only a simple profile drawing of the half headform used in USAARL's experiments.

The headform in the simulation was generated in the following manner. The engineering drawings of the full EN960 headform (the top half of which is apparently similar to the half headform) were used to generate a contour map of the full headform, which was reconstructed into a smooth-surfaced meshable object using Cubit. The model of the full headform was then cut down, using the profile drawings of the half headform to determine the appropriate cutplanes. The resulting headform model had the correct outer moldline, but was too massive, because the actual half-headform has a cavity in the bottom for the supporting arm. No data as to the exact geometry of this cavity was available, so

a simply shaped cavity was introduced into the headform model with a volume chosen to give the correct final mass. The model was then meshed.

A.3 Pads

Pad geometries for the crown impact simulations were determined by measuring the size 6 pads supplied by Team Wendy and Oregon Aero. Using Cubit, these geometries were rendered into meshable solids, which were then meshed.

Appendix B Pad experiments and model

B.1 Experiment

In order to obtain parameters for the material models in the simulations, unconfined compression tests were performed at different rates on each pad and on samples of each component foam material used in the Team Wendy, Oregon Aero, and Riddell pads. Due to the complex design of the Xenith pad, compression tests were performed only on the complete pad.

Complete pad tests were conducted at over a range of constant and variable strain rates. Component foam tests were conducted on right circular cylinders with nominal dimensions of ~1" diameter and ~0.25" height, cut from the foam pads. Tests were performed at low (~0.02/s), medium (~ 2.0/s) and variable high strain rates (~ 50/s at zero strain decreasing to ~ 4/s at 80% strain).

In order to assess the effects of the airtight coverings/coatings, compression tests were performed on the Team Wendy pad and the Riddell pad with and without the plastic covering, and on the Oregon Aero pad with and without the airtight coating. The covering around the Team Wendy pad and the coating on the Oregon Aero pad had a significant effect on the pad response. The inflatable covering around the Riddell pad had no effect on the pad compression response, due to relief channels that allow airflow between neighboring pads.

All material parameters used in our simulations were obtained from these tests performed at LLNL. The component foam tests were simulated using the same constant and/or variable loading strain rates that were used in the experiments. Material parameters for the individual foams were obtained by fitting the simulations to the experimental data. The complete pad tests were then simulated to verify that the fitted properties gave the appropriate response in a complete pad system.

B.2 Model

In order to save the time and effort required to develop and implement a viscoelastic foam model into PARADYN, an existing viscoplastic foam model developed by Puso [8] was used. The use of a viscoplastic foam model is justified even though the foams (including the Xenith pad) behave viscoelastically, because the viscoelastic response time is of the order of 1 second, which is very long compared to typical millisecond impact durations. Under these loading conditions, the response of an accurate viscoelastic model will be equivalent to the response of a viscoplastic model. Complete model details are given by Puso [8].

B.3 Pad Systems

B.3.1 Team Wendy

Team Wendy pads consist of a bilayer foam, with a softer layer adjacent to the head and a harder layer adjacent to the helmet shell, surrounded by an unattached polymer covering and then an unattached fabric covering. The effects of the fabric covering were neglected in this study.

Component foam tests utilized samples cut from various different pads. The hard foam samples were 1.00" diameter 0.26" thick cylinders. The soft foam samples were 1.00" diameter 0.27" thick cylinders. Figure 23 and Figure 24 show stress vs. strain for two fixed (0.02/s & 2.0/s) and one variable strain rate (monotonically decreasing from 50/s at zero strain to 4/s at 80% strain), for the hard and soft foams. The solid lines are the data. The lines with markers show the fit to the experimental data using the Puso model described above. The noise in the variable strain rate data is due to noise in the load cell. The most important feature of the data for the model to reproduce accurately is the strain rate dependence of the plateau stress. The figures show that the fitting parameters we have chosen provide a good fit to the plateau stress. At large strains, the Puso model collapses to a single stress-strain curve independent of strain rate, so there is some deviation of the model fit from the experimental data. However, the excellent fit to the high strain rate (variable) data shows that deficiency is unimportant, since a monotonically decreasing (engineering) strain rate is representative of typical impact kinematics.

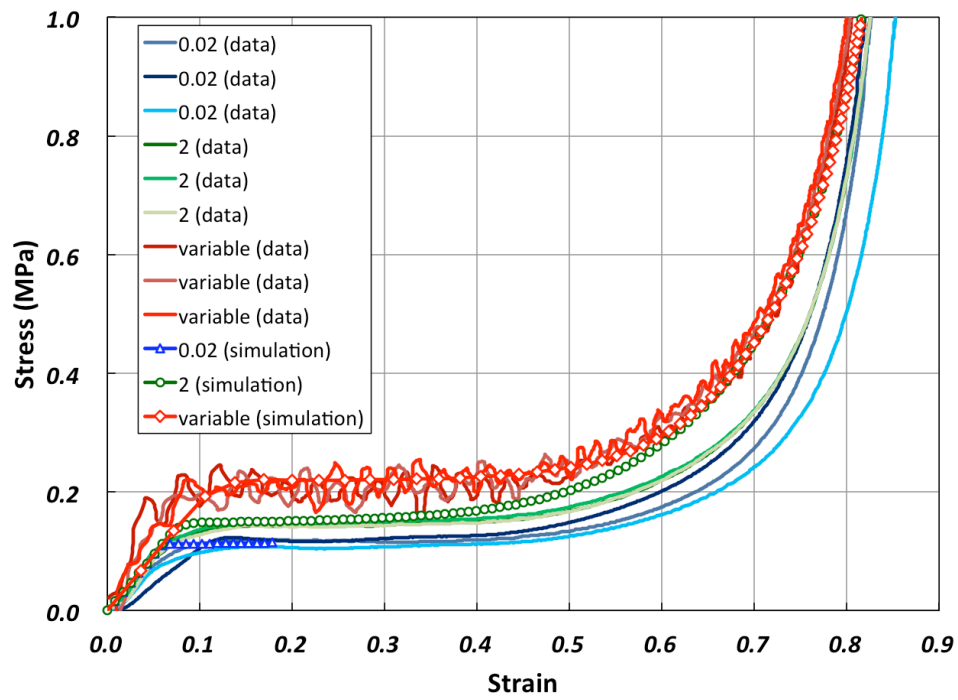


Figure 23 - Team Wendy hard foam data and model fit

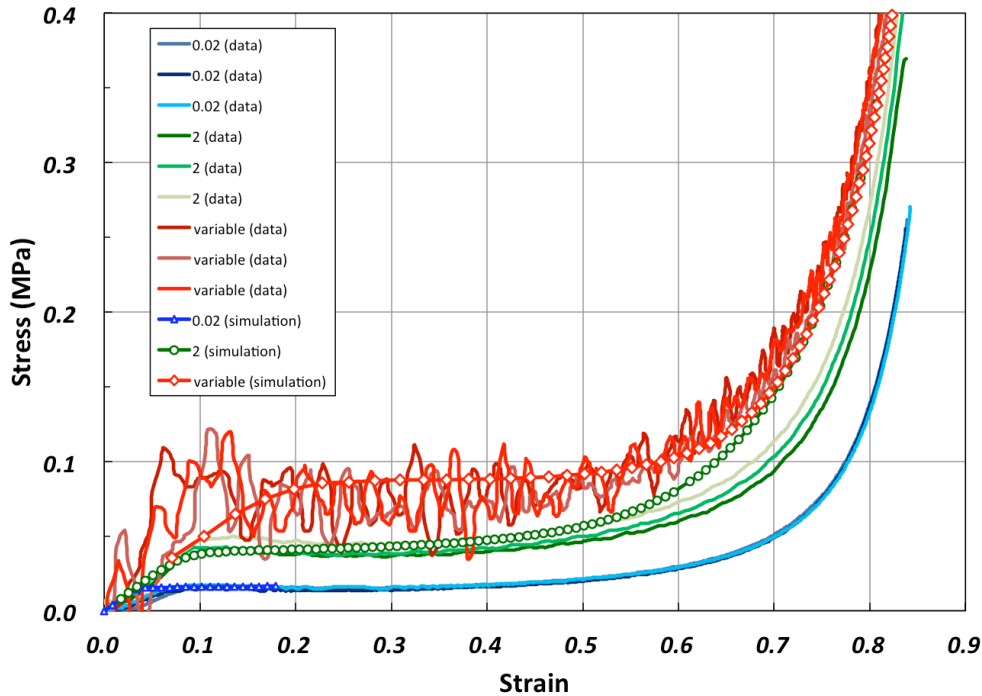


Figure 24 - Team Wendy soft foam data and model fit

Complete pad tests were conducted on the side pads. These are approximately rectangular with an area of 6.51 in^2 and thickness of $0.83''$ (with plastic covering) or $0.75''$ (without plastic covering). The soft and hard foams had equal thicknesses. Figure 25 shows the data and model prediction for the complete pad (using the properties fit to the component foam tests), with and without the airtight covering, for only the variable strain rate case ($17/\text{s}$ at zero strain to $2/\text{s}$ at 80% strain). When the airtight covering is removed, the model captures the pad response well. When the airtight covering is not removed, the effect of the trapped air is dramatic beyond 40% strain. To capture this effect, additional stiffness from an adiabatically compressed column of air was included in the model, as described in Appendix C, assuming 45% effective air-filled porosity of the foam.

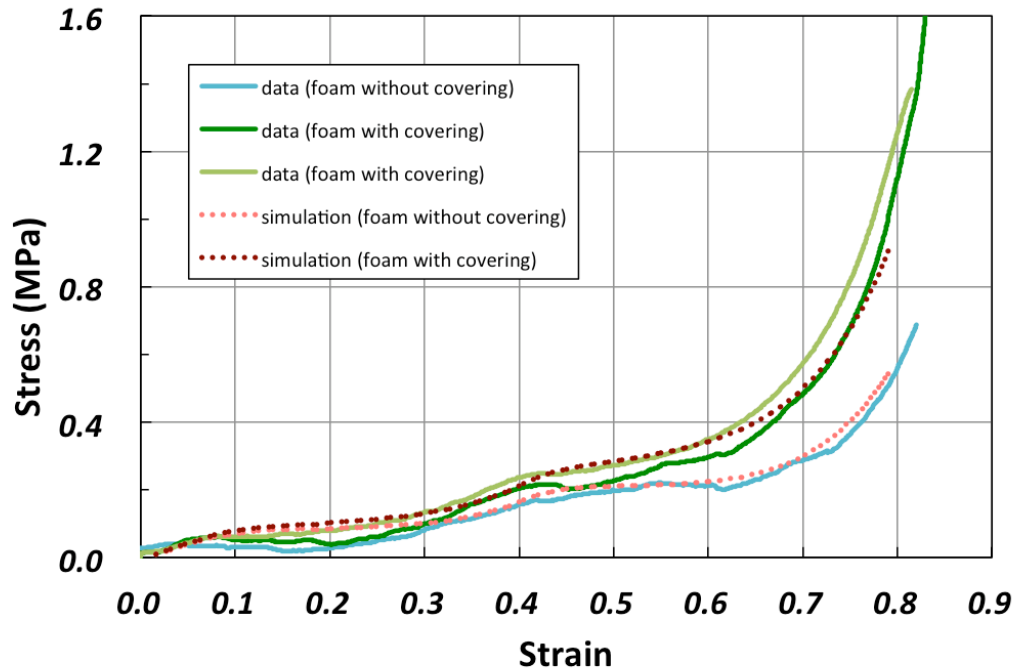


Figure 25 - Team Wendy pad data and model prediction

B.3.2 Oregon Aero

Oregon Aero pads consist of a bilayer foam with a softer layer adjacent to the head and a harder layer adjacent to the helmet shell, surrounded by a polymer coating bonded to the foam and an unattached fabric covering. The effects of the fabric covering were neglected in this study.

Component foam tests utilized samples cut from various different pads. The hard foam samples were 0.98" diameter 0.26" thick cylinders. The soft foam samples were 0.99" diameter 0.26" thick cylinders. Figure 26 and Figure 27 show stress vs. strain for two fixed (0.02/s & 2.0/s) and one variable strain rate (monotonically decreasing from 50/s at zero strain to 4/s at 80% strain), for the hard and soft foams. The solid lines are the data. The lines with markers show the fit to the experimental data using the Puso model described above. The noise in the variable strain rate data is due to noise in the load cell. The figures show that the fitting parameters we have chosen provide a good fit to the plateau stress.

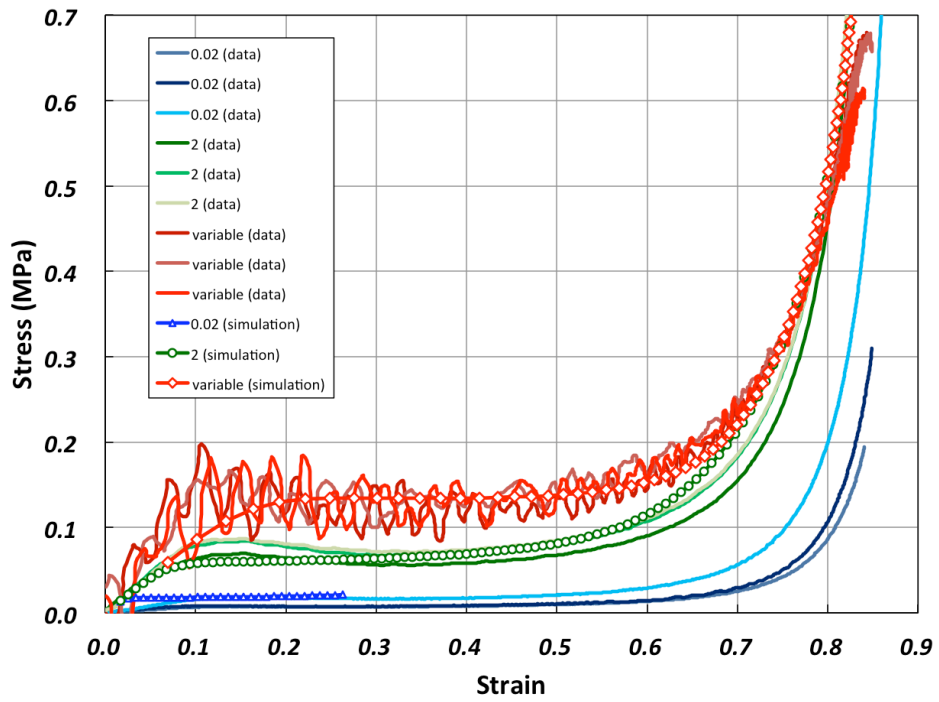


Figure 26 - Oregon Aero hard foam data and model fit

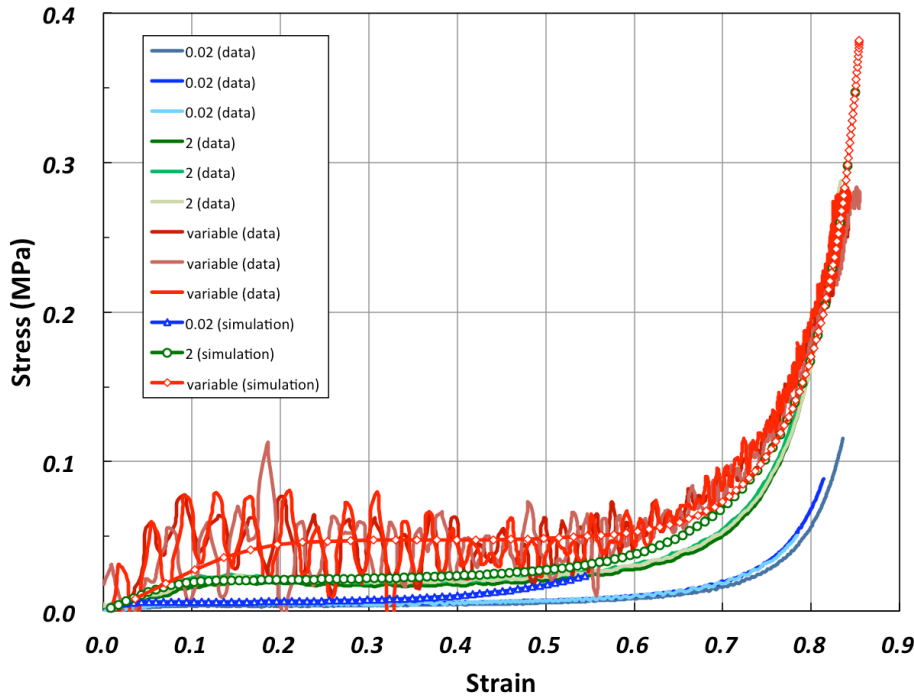


Figure 27 - Oregon Aero soft foam data and model fit

Complete pad tests were conducted on the side pads. These are approximately rectangular. Although #6 Oregon Aero pads, which are 0.75" thick, were simulated, and the individual foam samples described above were cut from #6 Oregon Aero pads, the full pad tests were conducted on thicker (#8) Oregon Aero pads due to sample availability.

Tests were conducted on both coated pads and pads on which the coating had been cut off. The coated pads had an area of 6.42 in² and thickness of 1.13". The uncoated pads had an area of 6.27 in² and thickness of 0.97". The pads were split between 39% soft and 61% hard foam (unlike thinner #6 Oregon Aero pads, which have a 50%-50% split). Figure 28 shows data and model prediction for the complete #8 Oregon Aero pad (using the properties fit to the component foam tests), with and without the airtight coating, for only the variable strain rate (15/s at zero strain to 2/s at 80% strain). When the airtight coating is removed, the model captures the pad response well. When the airtight coating is not removed, the effect of the trapped air is dramatic beyond 30% strain. To capture this effect, additional stiffness from an adiabatically compressed column of air was included in the model, as described in Appendix C, assuming 45% effective air-filled porosity of the foam.

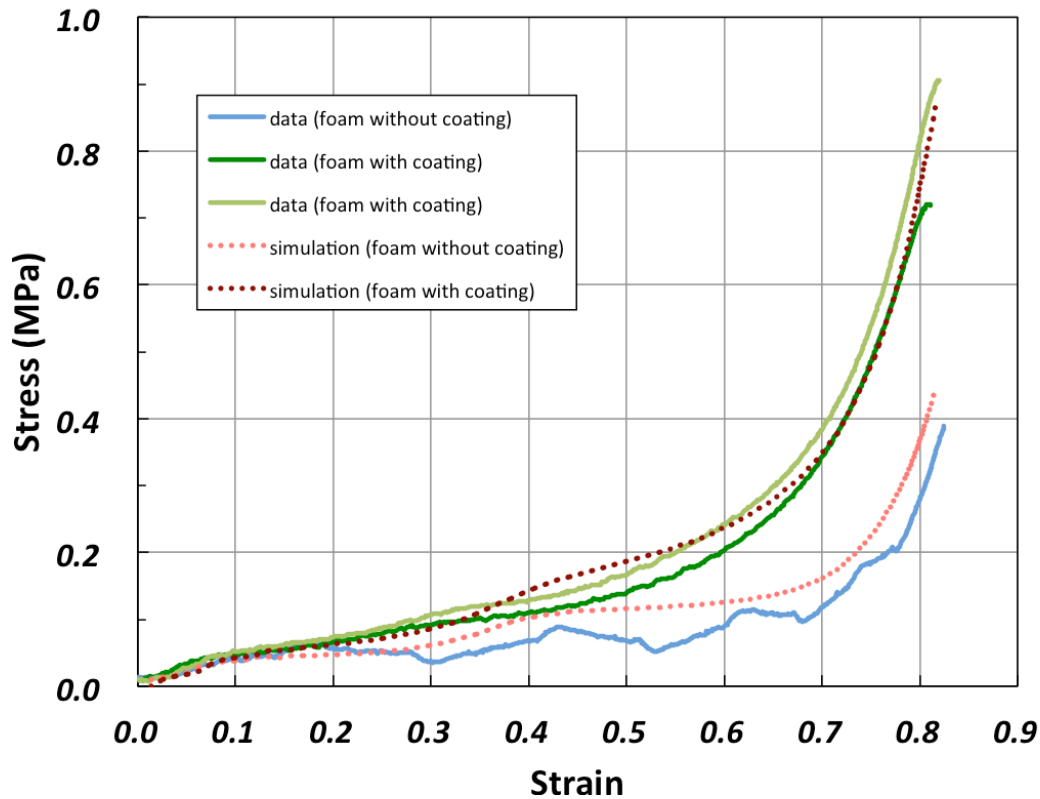


Figure 28 - Oregon Aero pad data and model prediction

B.3.3 Riddell

Riddell pads consist of a bilayer foam. The softer foam is adjacent to the head and is generally much thinner than the harder foam, adjacent to the helmet shell. The foam is surrounded by an inflatable polymer bag, with air relief channels that allow air to flow between neighboring pads.

Component foam tests utilized samples cut from all the different pads. The hard foam samples were 0.98" diameter 0.26" thick cylinders. The soft foam samples were 0.99" diameter 0.26" thick cylinders. Figure 29 and Figure 30 show stress vs. strain for two fixed (0.02/s & 2.0/s) and one variable strain rate (monotonically decreasing from 50/s at zero strain to 4/s at 80% strain), for the hard and soft foams. The solid lines are the data. The lines with markers show the fit to the experimental data using the Puso model described above. The noise in the variable strain rate data is due to noise in the load cell. The figures show that the chosen material properties provide a good fit to the plateau stress. Note that the Riddell hard foam is significantly harder than the Team Wendy (Figure 23) and Oregon Aero (Figure 26) hard foams.

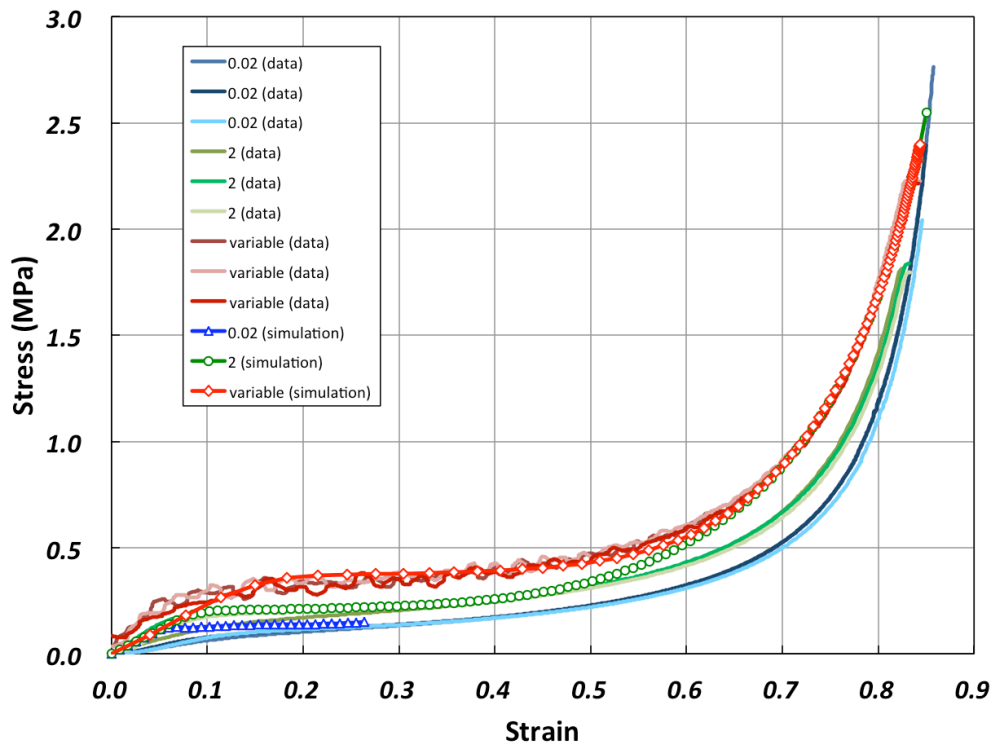


Figure 29 - Riddell hard foam data and model fit

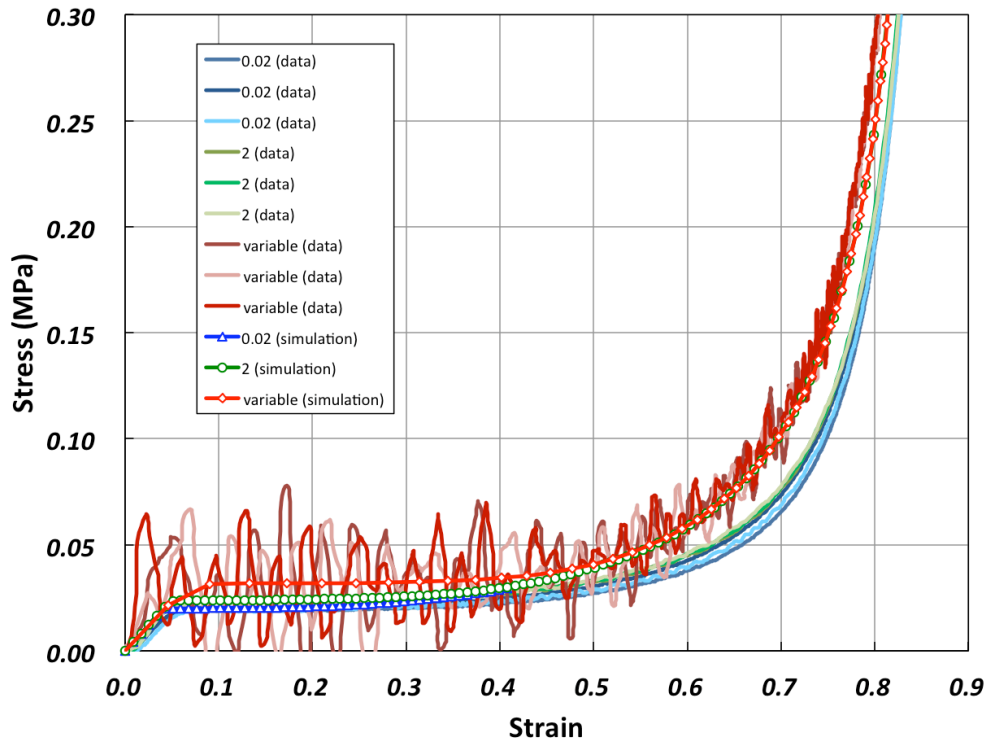


Figure 30 - Riddell soft foam data and model fit

Complete pad tests were conducted on the approximately rectangular pads. When removed from the inflatable covering, the pad had an area of 3.75 in² and thickness of 1.28", split between 29% soft foam and 71% hard foam. Tests were conducted on pads that had been removed from the inflatable covering, and on pads in an undamaged covering in both the inflated and un-inflated configurations. In both cases, the inflatable covering had no effect on the pad response, due to the air relief channels between adjacent pads. Figure 31 shows data and model prediction for the complete pad (using the properties fit to the component foam tests), for a fixed 8.4/s strain rate.

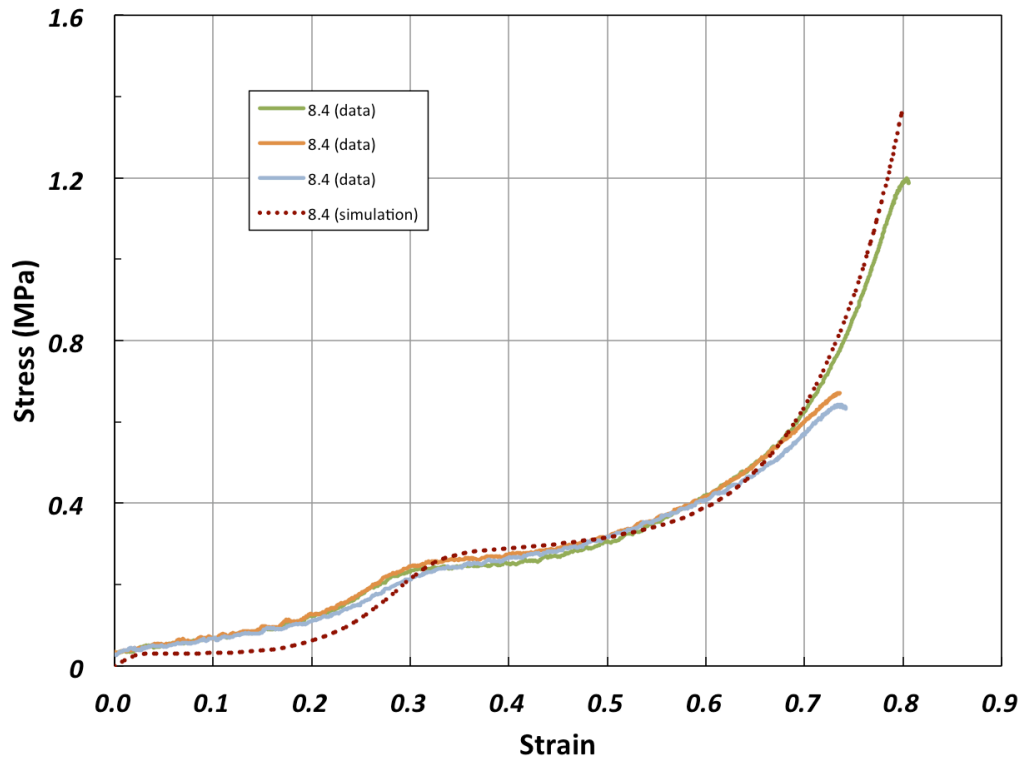


Figure 31 - Riddell pad data and model prediction

B.3.4 Xenith

The Xenith pad is a more complicated structure than the Team Wendy, Oregon Aero, or Riddell Pads. It consists of a hollow elastic structure designed to buckle under load, filled with air that can flow out through a small outlet. This adds rate-dependence to the response. The pad also incorporates a thin bilayer foam pad adjacent to the head, inside a rubber bag attached to the main pad structure. Only complete pad tests were conducted on the Xenith pad system; individual component tests were not performed.

The pads that were tested were 2" diameter and 1.45" thick, and are used in the crown of the Xenith "shock bonnet". Thinner (1.25" thick) pads are used elsewhere in the bonnet, but were not tested. The experimental data for the Xenith pad are shown in Figure 32, for low ($3\text{e-}4/\text{s}$) and medium ($\sim 10/\text{s}$) strain rates. The strain rate for the $3\text{e-}4/\text{s}$ data was constant throughout the loading, whereas the medium rate data was constant up to $\sim 65\%$ strain, after which the strain rate decreased to $5/\text{s}$ at 75% strain. The scatter of the $10/\text{s}$ data is due to the $0.001\text{-}0.003\text{'}$ measured differences in wall thicknesses of the tested pads, for which the stiffer pad had thicker walls. Note that a single 2" diameter Xenith pad has a stiffer response than the 5" diameter Team Wendy pad.

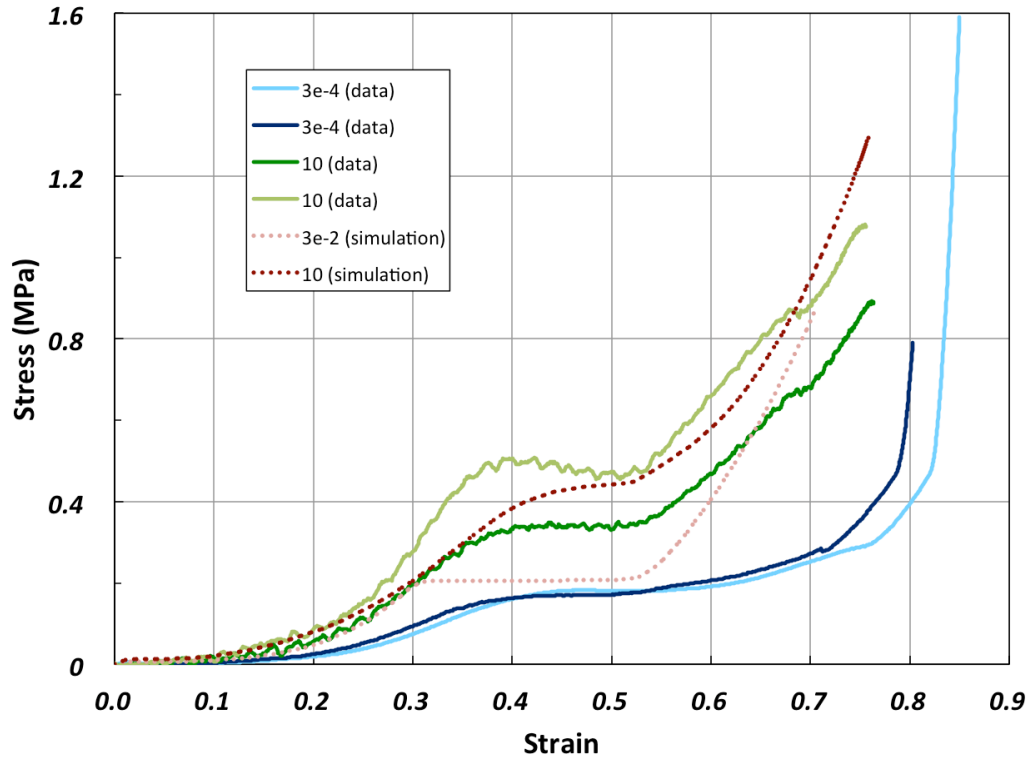


Figure 32 – Xenith pad data and model fit. A 0.03 s^{-1} strain rate was used to simulate the 0.0003 s^{-1} strain rate data, to reduce computational running time. Other than run time, the simulation differences are insignificant.

Figure 32 (solid lines) shows that the Xenith pad responds as if it is a bilayer foam, similar to those previously discussed, *e.g.*, see Figure 25, Figure 28, and Figure 31. In fact, the Xenith pad could be considered to be a foam with one very large single cell. The small airhole in the buckling part of the Xenith structure allows air flow in and out of the structure, but at a limited rate, retarding the unloading of the structure and giving the Xenith pad system an effectively viscoelastic response with a long time constant, analogous to the pure foam systems discussed previously. Consequently, we model the Xenith pad as a bilayer foam, and adjust the proportion and properties of the two foam materials to fit the response of the Xenith pad. This fit uses a 45% soft, 55% hard split, and is shown in Figure 32 (dotted lines).

B.3.5 d3o

The d3o pad material is composed of a single layer of a relatively dense foam. This foam is reportedly made of a rate-sensitive material.

The samples tested were 0.99" diameter 0.25" thick cylinders. The solid lines in Figure 33 show measured stress vs. strain for fixed strain rates of 0.02/s, 2.0/s, and 50/s, up to 50% strain.

This foam does not exhibit the characteristic response of the other foams, with a plateau followed by a densification. Hence, the Puso foam model was not appropriate to capture its response. Instead, the response of the material in the loading regime of interest could be represented by a rate-independent linear elastic material model. The line with open circles in Figure 33 shows the fit of such a model to the experimental data.

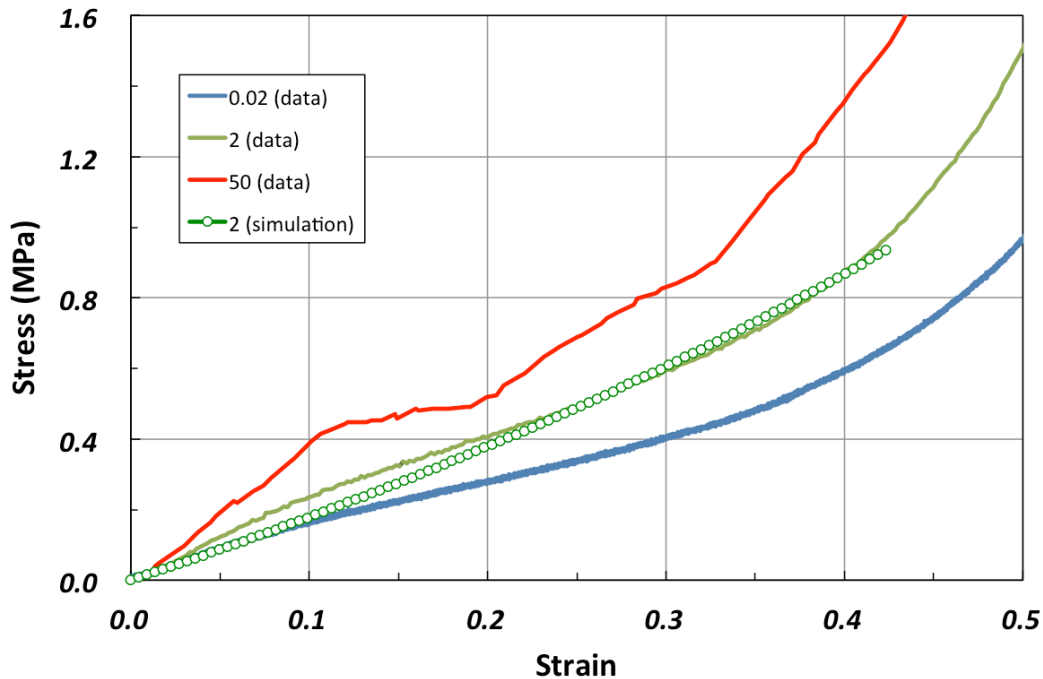


Figure 33 - d30 foam data and model fit

Because this material is so much stiffer than all the other materials we studied, even at 0.02/s, any calculated HIC would be very large regardless of any other details of the pad geometry. Consequently, we excluded d30 from the comparisons in this report. We believe that the utility of this material as a helmet pad is questionable.

Appendix C Modeling the Effects of Air

C.1 Basic Approach

As is discussed in Appendix B, two of the pad systems (Team Wendy and Oregon Aero) have an airtight covering or coating that has a non-negligible effect on the pad compression response, especially at large strains. This effect is visible in Figure 25 and Figure 28. When the covering/coating is intact, the response of the pad is stiffer at high strains than when the covering/coating is removed. Modeling only the two foams captures the response of the uncovered pad, but not the covered pad.

Rather than model the air flowing through and out of the foams as they are compressed and interacting with a deformable covering or coating, this effect is captured in the cylinder impact simulations by including an “air mesh” with a tailored material response in the model that acts in parallel with the actual foam to resist the impact. The elements that comprise this air mesh actually overlap, but do not interact with, the elements that comprise the foam. Like the foam elements, the air elements interact with their surroundings via slide surfaces. However, their transverse degrees of freedom are constrained so that the only mode of deformation they are allowed to undergo is uniaxial extension or compression.

The full helmet simulations of the USAARL crown impact tests use a similar methodology where an overlapping air mesh with a tailored response acts in parallel with the pads. However, because the direction of pad compression can vary in these simulations, the transverse degrees of freedom are not constrained. Instead, the air mesh is enclosed in an elastic membrane to constrain transverse expansion.

While these two approaches will produce slightly different responses (since the elastic membrane allows small transverse expansion of the air mesh, whereas the constrained degrees of freedom allow none), the differences in the loading regime of interest were shown to be negligible.

C.2 Air Material Model

Air is often modeled as a material with no shear strength and a volumetric response governed by a so-called gamma law equation of state, which, for adiabatic expansion or compression, states:

$$pV^\gamma = p_0V_0^\gamma,$$

where p and V are the pressure and the volume, and γ is the specific heat ratio. When $V_0 = 1$,

$$p = \frac{p_0}{V^\gamma}.$$

Although the compression of the pads is expected to be approximately an adiabatic process, this equation of state is not appropriate for use in the parallel air mesh for two reasons. First, it is too stiff—the air mesh has a greater volume than the actual air in the pad, because some of the pad volume is filled by the foam. Secondly, under zero deformation (*i.e.* $V = V_0 = 1$), it produces a non-zero pressure ($p = p_0 = \text{atmospheric pressure}$). If the simulations included the pressure applied by the surrounding air on all materials, then this would be appropriate; however, the effects of atmospheric air are neglected in the PARADYN analyses. As a result, a modified version of the air equation of state that satisfies the appropriate boundary conditions is needed:

$$p = \alpha p_0 \left(\frac{1}{V^\gamma} - 1 \right).$$

This equation of state will produce zero pressure (and stress) under zero deformation ($V = 1$). The parameter α is a number less than one that accounts for the fact that the volume of the air trapped in the pad covering is less than the total volume of the pad. It can be thought of to be a measure of the pad porosity, but is essentially a material parameter that can be tuned for a particular pad system.

In PARADYN, equations of state must be defined in one of several forms. One possible form is a linear polynomial, which has the form:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E.$$

Here E is the internal energy (per unit reference volume), and μ is the compression:

$$\mu \equiv \frac{\rho}{\rho_0} - 1 = \frac{1}{V} - 1.$$

This equation of state will yield the adiabatic response given above, if the following constants are used:

$$C_0 = -(\gamma - 1)E_0,$$

$$C_1 = \alpha p_0 \gamma - (\gamma - 1)E_0,$$

$$C_2 = C_3 = 0,$$

$$C_4 = C_5 = \gamma - 1, \text{ and}$$

$$C_6 = 0 .$$

The value of E_0 , the internal energy in the reference state, is arbitrary. For convenience, choosing $E_0 = 0$ gives a very simple equation of state:

$$C_0 = C_2 = C_3 = C_6 = 0 ,$$

$$C_1 = \alpha p_0 \gamma , \text{ and}$$

$$C_4 = C_5 = \gamma - 1 .$$

Appendix D The Head Injury Criterion

D.1 Definition

The Head Injury Criterion [HIC] is a well established metric developed from experimental data that quantifies the severity of an impact [6]. It does not take head rotation into account; it quantifies only the severity of linear acceleration with respect to the likelihood of injury. It is used by the automotive industry to evaluate vehicle safety.

For a given linear acceleration history $a(t)$, the HIC is defined as:

$$HIC = \max_{t_1, t_2} \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \right\}.$$

The acceleration a must be in G's. The initial time t_1 and the final time t_2 must be in seconds. Furthermore, a bounding time (usually 15 ms) generally used; *i.e.* $t_2 \leq t_1 + 0.015$.

In other words, the HIC is computed from the worst possible time period with length less than 15 ms, and is the average acceleration during that time period raised to the 2.5 power, times the length of the time period.

Note that larger accelerations do not necessarily result in a higher HIC; if the large accelerations are very short in duration, the corresponding HIC (and the probability of injury) will be less than for lower accelerations that last much longer.

The value of the HIC can be related to the probability of injury [9]. A HIC of 1000 is considered to be life threatening and corresponds to an 18% chance of severe injury, a 55% chance of serious injury, and a 90% chance of moderate injury in the average adult. A HIC of 600 is considered to be the threshold for moderate injury and corresponds to an 18% chance of serious injury and a 50% chance of moderate injury. A HIC of about 300 is the threshold for minor concussions (approximately a 50% chance).

D.2 Advantages over Peak Acceleration

HIC is a more useful metric for comparison of pad performance than peak acceleration. Larger peak accelerations over very short durations are actually less dangerous than lower accelerations over longer durations. The HIC was developed to capture this effect.

Furthermore, peak acceleration based metric is very sensitive to experimental or computational variations. For example, a set of simulations was performed simulating a crown impact of an ACH shell with Team Wendy pads and a 5 kg

headform. Depending on the amount of plasticity assumed to occur within the helmet at the point of impact, the peak acceleration reported by the simulation varied between 126 and 146 G's. However, the HIC only varied from 435 to 440. The HIC was far less sensitive to a difficult to characterize and probably relatively unimportant material parameter.

Finally, acceleration data, whether obtained from an experiment or reported by a computational simulation, is generally very noisy and must be filtered. However, the peak acceleration in either case is strongly dependant on the filtering frequency. Two experiments could produce very similar acceleration histories with similar likelihoods of injury, but if the experimental data were filtered at different frequencies, dramatically different peak accelerations could be obtained. One particular acceleration history, shown in Figure 34 has a peak acceleration of 153 G's when unfiltered, and a peak acceleration of 126 G's when filtered at 1,500 Hz.

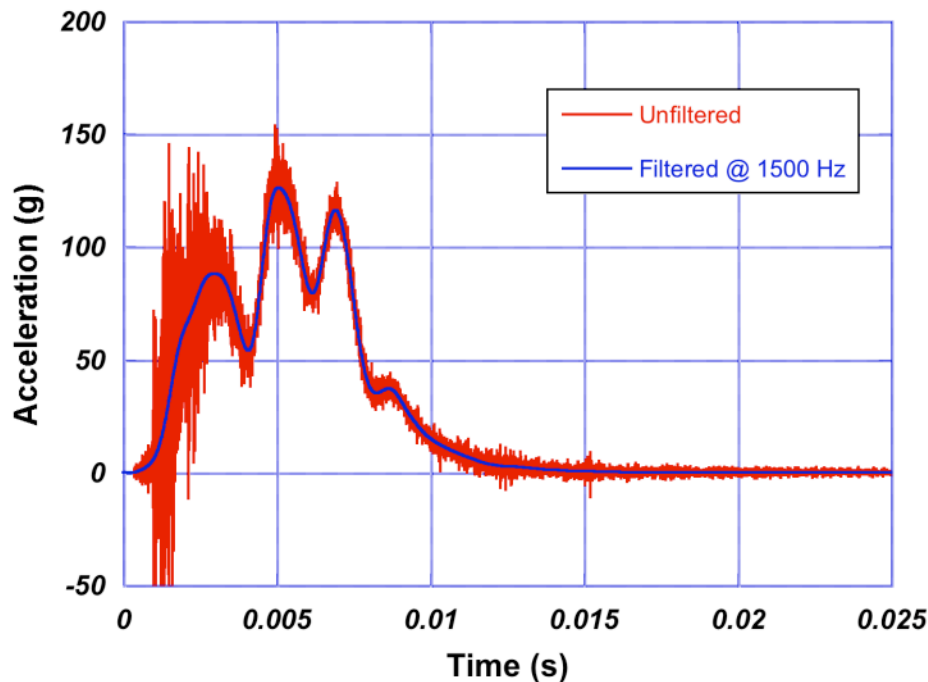


Figure 34 - Acceleration history for a particular crown impact, showing the effect of filtering on peak acceleration

The HIC is far less sensitive to filtering frequency. This same acceleration history has a HIC of 441 when unfiltered and 440 when filtered.

For these reasons, this study uses HIC to compare pad performance, not peak acceleration.